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WELDING RESEARCH

29, PARK CRESCENT, LONDON, W.1

ASSOCIATION NOTES

B.W.R.A. Summer School of Welding

The third Summer School of Welding will be held at Ashorne Hill, near Leamington Spa, Warwickshire, from Monday, 27 April, until Saturday, 2 May, 1953.

This year the general theme of the School is welding fabrication and production and the various aspects will be covered in logical sequence during the course. However, to assist industrial organisations whose staff may be more particularly interested in one aspect of welding, the School has been divided into certain groups. Students will be given lectures of general interest, usually in the morning, followed in the afternoon by lectures on more specialised subjects under five group headings:

Group A: Aircraft Industry
Group B: Shipbuilding Industry
Group C: Structural Engineering
Group D: Automobile and Sheet Metal Industries
Group E: General Engineering.

As vacancies are limited, it is suggested that those wishing to attend the School, or send representatives from their organisations, should communicate as soon as possible with the Secretary, B.W.R.A. Summer School of Welding, British Welding Research Association, 29, Park Crescent, London, W.1, requesting the necessary application forms and full particulars.

Multi-Lingual Dictionary

We learn from the International Institute of Welding that considerable progress has been made in the preparation of a dictionary of welding terms in ten different languages. The first section on terms relating to gas welding is now complete and it is proposed to print this in Danish, Dutch, English, Finnish, French, German, Italian, Norwegian, Spanish and Swedish. This section should be available in the late spring and all enquiries for copies should be sent to the Institute of Welding, 2, Buckingham Palace Gardens, London, S.W.1.

As a result of a subsidy from the Union of International Engineering Organisations and the kindness of the Société Suisse de l'Acétylène, who have kindly undertaken to see this first section through the press, it is hoped that the copies will be available at fairly low cost which, we understand, will be in the region of 15s.

Resistance Welding

This issue of *Welding Research* is entirely devoted to research reports on various aspects of the resistance spot welding process, one of the most mechanised means of joining metals and used extensively in industries where the mass production technique is employed. Hand-in-hand with the progress towards the fully mechanised production line and the extensive use of the resistance welding process, must go an understanding of the effect of the process variables on weld quality so as to ensure production of high quality welds.

For any given material, the "variables" of interest in spot welding are thickness, surface condition, electrode size, electrode tip load, welding current and duration. The preparation of a code of practice in which recommended welding conditions are given requires a knowledge of the effect of these welding conditions on weld quality, over a wide range of conditions. A report in this issue of the journal on the spot welding of $\frac{1}{8}$ in. and 24 s.w.g. low-carbon steel, presents the results of research work required for a revised code of practice now being prepared by the B.W.R.A. for spot welding low-carbon steel within the range 24 s.w.g. to $\frac{1}{8}$ in. thickness. In the thicknesses 24 to 14 s.w.g., the work has been confined to clean, bright, deep-drawing quality steel sheet, which is widely used in the motor body industry—probably the largest user of the spot welding process.

The code of practice will give recommendations based on the use of welding machines of the conventional single-phase A.C. pedestal type and gun welder which are almost exclusively used in car body construction, although interesting developments are now taking place with the multiple electrode press type spot welding machines.

In the work on spot welding of steel extensive use has been made of the air-cored toroid and integrating circuit method of current measurement. Another interesting aspect of this work has been the use of statistical methods in comparing welding conditions for both 24 s.w.g. and $\frac{1}{8}$ in. thick steel. It has been shown that a considerable latitude in welding conditions is possible in welding $\frac{1}{8}$ in. thick material and the selection of optimum welding condition is on a somewhat arbitrary basis. The range of suitable welding conditions for 24 s.w.g. material is naturally more limited but the conditions for the formation of high-quality welds can be readily achieved under production conditions.

Further work on the spot welding of mild steel has been completed on material of $\frac{3}{16}$ in. and $\frac{1}{4}$ in. thickness, and these results will be published in due course. The present work for the code of practice has been almost entirely on a rimming quality low-carbon deep-drawing steel. The RR.6 Committee who control this work has realised the importance of investigating other low-carbon steels, e.g. fully killed and stabilised steels, and basic Bessemer steel of differing nitrogen content. Much of this work has already been completed and will be made available during the year.

Control of weld quality in resistance welding is essentially bound up with the control of the variables of the machine itself and a means must be available of recording, checking and examining these variables during production. Simple instruments are commercially available for the measurement of secondary current output of A.C. machines, e.g. peak reading valve-voltmeter and impulse ammeter for current magnitude and cycle recorder for current duration. The valve-voltmeter is not suitable for use with machines employing phase shift for heat control, but the impulse-ammeter can be calibrated in terms of r.m.s. current under these conditions.

The direct reading meter instruments are generally not satisfactory when non-sinusoidal current waves are used for welding and electro-magnetic and cathode-ray oscillograph methods have been developed to obtain a true record of current. The increasing application of stored-energy and frequency converter type machines, giving widely different current wave shapes, has provided an incentive to the development of suitable methods of recording secondary current and a report on methods used with condenser discharge equipment, described in this issue of *Welding Research*, will be of particular interest.

The method used for simultaneous measurement of secondary current and electrode load cycle is described in detail and the ability to make simultaneous measurements is an essential requirement with machines employing the dual type of load cycle, in which the electrode load is rapidly increased to consolidate the weld. Although the methods described were developed for condenser discharge machines, they are satisfactory for other types of machine with different current wave shapes. For example, the air-cored toroid and electrical integrating circuit have been standardised in the B.W.R.A. engineering laboratories for use with the following machines:

1. Conventional A.C. machine with electro-magnetic contactor and heat control by transformer tap switch;
2. Conventional A.C. machine with heat control by phase shift (ignitron contactor);
3. Conventional A.C. machine with heat control by automatic phase shift (slope control);
4. Stored-energy machines of the condenser discharge type; and
5. Three-phase frequency converter machine.

The accuracy of the recorded wave shape for these machines can be readily assessed mathematically and is shown to be dependent on the circuit values of the integrating circuit and the frequency of the current pulse.

The ability to measure machine output is of great value in the calibration of equipment and in the periodic checking of welding conditions. In the past, oscillographic methods have been considered as a research tool only to be used in the laboratory, but the increasing complexity of machines for special applications has led to an appreciation of C.R.O. and E.M.O. methods for accurate measurement under production conditions. Engineers using A.C. machines with slope control or the 3-phase frequency converter machines will welcome the detailed report on instrumentation.

The International Institute of Welding have amended a statement in the report of Commission 10-11 which we published under the section Association Notes in the previous issue of *Welding Research*, December, 1952.

Under the section Memorandum on Stress Relieving, page 105, *column* 2, *second paragraph, the last sentence should read:* "Restraint of the weld is mentioned as a factor that is desirable to take into account and is implicit in British Codes," etc., etc.

SPOT WELDING OF LOW-CARBON STEELS—24 S.W.G. AND $\frac{1}{8}$ IN. THICK

The research programme on the spot welding of these two thicknesses of low-carbon steel was undertaken at the request of the F.R. 6 Committee of the B.W.R.A. for the purpose of extending the range of the existing code of practice which covered thicknesses of material in the range 20 to 14 s.w.g.

The two reports of this work, FR. 6/31 and FR. 6/33, were issued to Members of the Association during October, 1952, and are combined here as, Part I on the welding of the 24 s.w.g. material, and Part II on the welding of the $\frac{1}{8}$ in. material. The code of practice is now being revised to include this work and will be published by the Association as a Technique Memorandum T.21A.

By H. E. DIXON, M.Sc., A.I.M., and J. E. ROBERTS, M.Eng., A.I.M.

Part I.—Spot Welding of 24 s.w.g. Low-Carbon Steel

SYNOPSIS

The experimental technique used to determine the "optimum" spot welding conditions for 24 s.w.g. mild steel sheet is described. The selection of the welding conditions has been made by examination of the mean strength, consistency (measured by standard deviation), electrode indentation and sheet separation.

The suitability of the recommended conditions has been checked by making over 2,000 welds for each condition, the mean strength and standard deviation being determined at known intervals throughout the tests.

INTRODUCTION

Information was required on the effect of a wide range of welding conditions on the quality of spot welds in a low-carbon steel. The variables examined were electrode tip size, electrode tip pressure and welding current magnitude and duration. The work was planned in three stages: (1) *Preliminary*—a broad survey of the effect of the welding variables using many conditions, but a few welds only per condition; (2) *Main Series*—a detailed investigation of a limited number of conditions selected from the results of the preliminary tests; and (3) *Electrode Life Tests*—using "optimum" conditions selected from the main series.

MATERIAL AND SPECIMEN SIZE

The material used was deep-drawing quality basic open-hearth mild steel to specification S.84, supplied as a 3 in. wide coil. The composition of the steel was as follows:

C	.. 0·075 per cent.	Sn	.. 0·078 per cent.
Si	.. Not given	Cu	.. 0·115 ,,
Mn	.. 0·036 per cent.	Ni	.. 0·137 ,,
S	.. 0·032 ,,	Cr	.. 0·010 ,,
P	.. 0·020 ,,		

and the mechanical properties:

Tensile strength	25·25 tons per sq. in.
Elongation	28·4 per cent. on 2 in.
Hardness	120-126 V.P.N. (10 kilo load)

The surface of the material was smooth and free from rust, and no further surface treatment other than degreasing was required before welding.

For testing the welds both shear and tensile specimens were produced. The shear specimens were strips 3 in. by $\frac{3}{8}$ in. for the preliminary series of welds, the width being increased to $\frac{3}{4}$ in. for the main series of consistency tests. The test pieces were overlapped by a distance equal to their width, and a single spot made in the centre of this overlap. The tension test specimens were also made up of two pieces 3 in. by $\frac{3}{4}$ in. at right-angles to one another and forming a symmetrical cross. The weld was made at the centre of the intersection.

WELDING MACHINE AND EQUIPMENT

A 25 kVA spot welding machine was used, fitted with thyratron timer and electro-mechanical contactor. The timer was checked by taking oscillograph records of the secondary current to obtain the settings required to give times of 5, 8, 10, 15, 20, 30 and 50 cycles. The minimum time possible with this machine was 5 cycles and tests at shorter times were made with another machine employing a synchronous timer and ignitron contactors. (See acknowledgment.)

The initiation of the welding current was governed by an air pressure switch set to operate when the maximum required electrode tip load was attained. The welding load was checked statically before welding by means of a load measuring unit and the secondary current recorded during welding by means of an air-cored toroid, the output of which was integrated, fed to a cathode ray oscillograph and photographed. (This method of current measurement has been described fully elsewhere.[1,2])

Standard $\frac{3}{4}$ in. shank diameter electrodes of copper chromium alloy were used throughout the tests, the face angle being 30 deg. and the tip diameter being varied as required.

WELDING METHOD AND TESTING PROCEDURE

The specimens were of the single spot type as described above, and were located between the electrodes by means of a simple jig made of "Tufnol" and clamped on to the electrode holder. The use of the jig ensured that the overlap of the shear specimens was constant, and that the weld was on the centre line of the two strips being joined. Similarly, for tension test specimens, the jig ensured that the two strips crossed at right-angles and centred the position of the weld.

The shear specimens were tested, using a motor-driven 3-ton Avery tensile testing machine on the 0·75 ton range, with a straining rate of 0·2 in. per minute and the method of failure was noted. Tension testing was done on the same machine, with the specimen held in clamps to minimise sheet distortion, accurate location for an axial pull on the weld being ensured by jig drilled holes in the specimen.

Specimens from each condition of the main series were sectioned, polished and etched to show the structure of the weld and for measurement of indentation and penetration.

PRELIMINARY SERIES

Tests were made with electrodes of $\frac{3}{32}$, $\frac{1}{8}$ and $\frac{5}{32}$ in.* tip diameters and three values of load were used for each size of electrode based on tip pressures of 10,000, 12,500 and 15,000 lbs. per sq. in.†

The current values used for each electrode-load combination are given in Table I. Weld times of 5, 10, 15, 20, 30 and 50 cycles were used for each current value, giving a total of 316 conditions. Three welds were made and tested in shear for each condition. The average strength of each group of three welds was then plotted against current duration. This gave a series of curves relating weld strength, current magnitude and duration for each electrode size and load. A typical example is shown in Fig. 1 for $\frac{5}{32}$ in. electrodes with a tip load of 190 lb.

The curves showed that under nearly all the conditions examined, if a time of 5 cycles was sufficient to produce a weld, no advantage in strength was obtained by prolonging the current, though some improvement in consistency might occur. The effect of load, as shown by these graphs, was slight, although again it might influence the strength consistency. It should be noted, however, that the specimen width was $\frac{1}{8}$ in. which was insufficient for many of the welds made at long weld times and caused the sheet to fail before the weld. The strength values obtained under these conditions thus did not give a true indication of the weld size.

Visual examination was used to determine conditions obviously unsuitable due to excessive indentation and splashing during welding.

MAIN SERIES

Welding Conditions

The welding conditions included in this series were selected from consideration of the results of the preliminary series. Electrode loads corresponding to tip pressures of 10,000 and 15,000 lb. per sq. in. only were selected since the preliminary results suggested that the effect of tip pressure was generally small. Three current values were used with each electrode size and tip pressure combination, the highest value being the maximum current that could be used without danger from weld splashing or excessive indentation, and the lowest value the minimum current necessary to produce welds of adequate strength. The remaining current value was approximately the average of the maximum and minimum values. Weld times of 5, 10 and 15 cycles only were tested for each current since the effect of duration on strength was small.

Twenty-two specimens were welded for each of the conditions selected in this manner, twenty being tested in shear and two sectioned for measurement of indentation and weld penetration.

Table I.—Details of Welding Conditions Examined in Preliminary Series

Electrode Tip Size (in.)	Electrode Tip Load (lbs.)	Mean Welding Current (kilo. amps.)	Weld Time (Cycles 50 c/s)
$\frac{3}{32}$	70, 90	4·2, 4·3 4·6, 5·0	5, 10, 15, 20, 30 and 50 for each current.
	105	4·2, 4·3 4·6, 5·0 5·2	
$\frac{1}{8}$	120,150,	4·2, 4·3 4·6, 5·0 5·2, 6·4	
	230	4·2, 4·6 5·0, 5·2 6·4, 7·8	
$\frac{5}{32}$	190, 240	4·2, 4·6 5·0, 5·2 6·4, 7·8 8·5	
	290	4·6, 5·0 5·2, 6·4 7·8, 8·5	

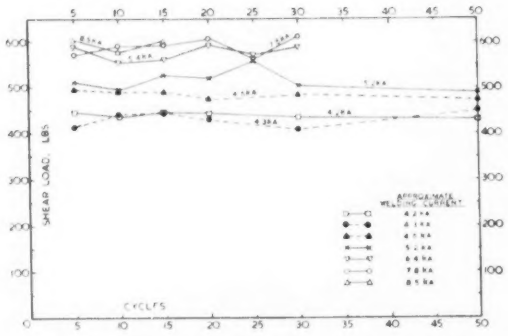

Fig. 1. Electrode tip diameter $\frac{5}{32}$ in.—load 190 lb.

Examination of Results

The values of the welding variables used in the main series of tests and the average strength, coefficient of variation, etc., are given in Table II.

The consistency of shear strength results has been expressed by means of the coefficient of variation,‡ since this provides

* $\frac{5}{32}$ in. is just greater than $\sqrt{t}$, where t is the sheet thickness in inches.

† By accident a load of 230 lb. was used with $\frac{1}{8}$ in. tip diameter electrodes corresponding to a tip pressure of 18,750 lb. per sq. in. This value was used throughout the preliminary tests before the error was discovered.

‡ If x is the strength of an individual weld, $\bar{x}$ the mean weld strength, and n the number of individual results, then the coefficient of variation is given by $\gamma = \frac{\Sigma (x-\bar{x})^2}{n-1} \times \frac{100}{\bar{x}}$

Table II.—Welding Conditions with Weld Strengths and Consistencies for Spot Welds in 24 s.w.g. Steel Sheet

Electrode Diameter (in.)	Electrode Load (lbs.) and Group No.	Welding Current (kA)	Weld Time (Cycles 50 c/s)	Mean Shear Strength (lbs.)	Coefficient of Variation*	Mode of Failure†	Remarks
$\frac{3}{32}$	70 (1)	4·1	15	515	3·0	TS-SF	All welds show interfacial splash. Rather deep indentation at long times with noticeable sheet separation and welds of good shape
		4·1	10	515	3·3	TS-SF	
		4·1	5	490	4·2	TS-SF	
$\frac{3}{32}$	70 (2)	3·6	15	505	2·2	TS	Splashing on all welds. Deep indentation
		3·6	10	505	3·9	TS	
		3·6	5	465	2·8	TS	
$\frac{3}{32}$	70 (3)	3·4	15	470	3·3	TS	Welds of good shape and consistency, but with deep indentation
		3·4	10	470	3·3	TS	
		3·4	5	440	3·2	TS	
$\frac{3}{32}$	105 (4)	4·8	15	530	4·4	PS-TS	Severe splashing and deep indentation
		4·8	10	515	3·5	PS-TS	
		4·8	5	500	4·0	PS	
$\frac{3}{32}$	105 (5)	4·0	15	480	4·3	TS-SF	Splashing from most welds. Indentation
		4·0	10	500	3·1	PS-SF	
		4·0	5	475	3·2	TS	
$\frac{3}{32}$	105 (6)	3·3	15	460	4·1	PS	Welds of good shape and consistency. No splashing. Indentation greater than 10 per cent. for 15 cycle welds only
		3·3	10	445	2·9	PS	
		3·3	5	420	4·0	TS	
$\frac{1}{8}$	120 (7)	5·4	15	560	3·4	TS-SF	Splashing from most welds. Indentation relatively deep
		5·4	10	565	3·3	SF	
		5·4	5	535	2·7	SF	
$\frac{1}{8}$	120 (8)	4·2	15	495	2·4	PS	Weld appearance reasonable
		4·2	10	490	3·7	TS-SF	
		4·2	5	480	4·2	TS	
$\frac{1}{8}$	120 (9)	3·4	15	415	3·4	SH	Small welds, but otherwise satisfactory
		3·4	10	410	4·5	SH-PS	
		3·4	5	420	2·3	SH-PS	
$\frac{1}{8}$	230 (10)	5·2	15	525	1·9	PS	Weld appearance satisfactory. Indentation greatest on 15 cycle welds, not excessive
		5·2	10	515	3·0	PS	
		5·2	5	515	2·7	PS	
$\frac{1}{8}$	230 (11)	4·3	15	425	7·2	SH	Small welds but otherwise satisfactory
		4·3	10	445	3·1	PS	
		4·3	5	440	3·9	PS	
$\frac{1}{8}$	230 (12)	4·1	15	365	17·5	SH	Poor consistency. Only partially fused
		4·1	10	340	20·0	SH	
		4·1	5	360	5·9	SH	
$\frac{5}{32}$	190 (13)	7·8	15	620	4·5	ST-TS	Splashing and deep indentation
		7·8	10	600	3·6	SF-TS	
		7·8	5	610	4·1	SF	
$\frac{5}{32}$	190 (14)	5·2	15	540	2·7	PS-TS	Good appearance
		5·2	10	550	1·6	SF	
		5·2	5	530	1·5	SF	
$\frac{5}{32}$	190 (15)	4·3	15	430	4·7	SH	Only partially fused
		4·3	10	485	6·2	SH	
		4·3	5	430	4·5	PS	
$\frac{5}{32}$	290 (16)	8·4	15	670	2·0	SF	Splashing on most welds
		8·4	10	655	2·2	SF	
		8·4	5	610	3·2	SF	
$\frac{5}{32}$	290 (17)	5·8	15	505	2·2	PS-TS	Good appearance
		5·8	10	510	3·0	PS	
		5·8	5	510	2·0	TS-PS	
$\frac{5}{32}$	290 (18)	4·3	15	340	9·0	SH	Very variable. Only partly fused
		4·3	10	325	20·2	SH	
		4·3	5	290	32·2	SH	

STATISTICAL TERMS.

* *Variance* σ^2. This may be defined as the sum of squares of the deviations of the strengths from their mean, divided by one less than the total number of observations. *Standard Deviation* σ is given by the square root of variance.

Coefficient of Variation is given by: $\frac{\text{Standard Deviation}}{\text{Mean Strength}} \times 100$

† PS = Pulled slug.
SH = Weld sheared.
SF = Sheet failed remote from weld usually near grips.
TS = Vee-like failure of sheet from edge of weld to both edges of strip.
SF-TS = Mixed SF and TS failure.
SH-PS = Mixed SH and PS failure.

a useful basis for comparing results. An arbitrary scale has been drawn up for the significance of values of the coefficient: values less than 5 are considered to indicate very good consistency, from 5-10 satisfactory, from 10-15 moderate, and above 15 poor.

The results given in Table II show that there are only a few of the conditions which give poor consistency. Examination shows that where poor consistency occurs, this can be attributed to the weld size being much smaller than the electrode tip diameter, an inherently unstable condition which is undesirable in spot welding.

A more rigorous selection of welding conditions can be made by considering weld appearance, i.e. indentation, sheet separation and nugget penetration, as well as strength and consistency.

The dimensions of the "ideal" weld have been suggested in the existing B.W.R.A. Technique Memorandum T.21 for 20 to 14 s.w.g. thick material, and these are illustrated in Fig. 2 (*a*), i.e. the indentation and sheet separation are not greater than 10 per cent., and nugget penetration 60-80 per cent. of sheet thickness, and nugget diameter within ± 5 per cent. of electrode tip diameter.

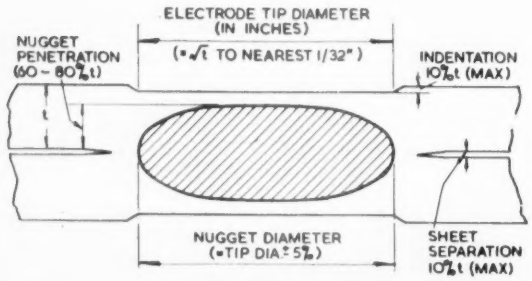

Fig. 2 (*a*). Dimensions recommended in existing memorandum (T.21) for 20, 18, 16 and 14 s.w.g. steel.

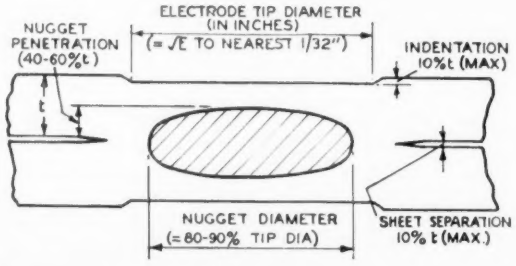

Fig. 2 (*b*). Recommended dimensions for welds in 24 s.w.g. sheet.

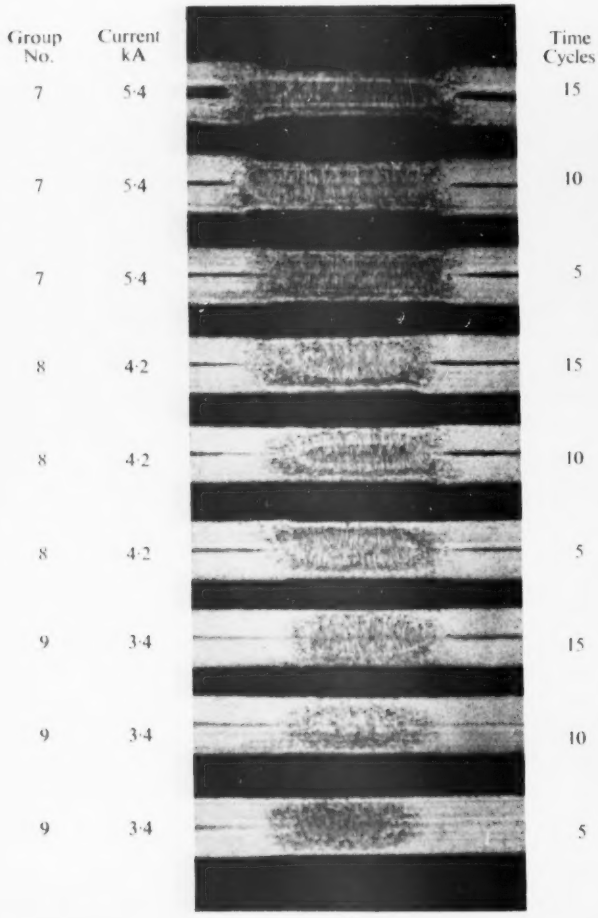

Fig. 3. $\frac{1}{8}$ in. diameter electrode tip—120 lb. load.

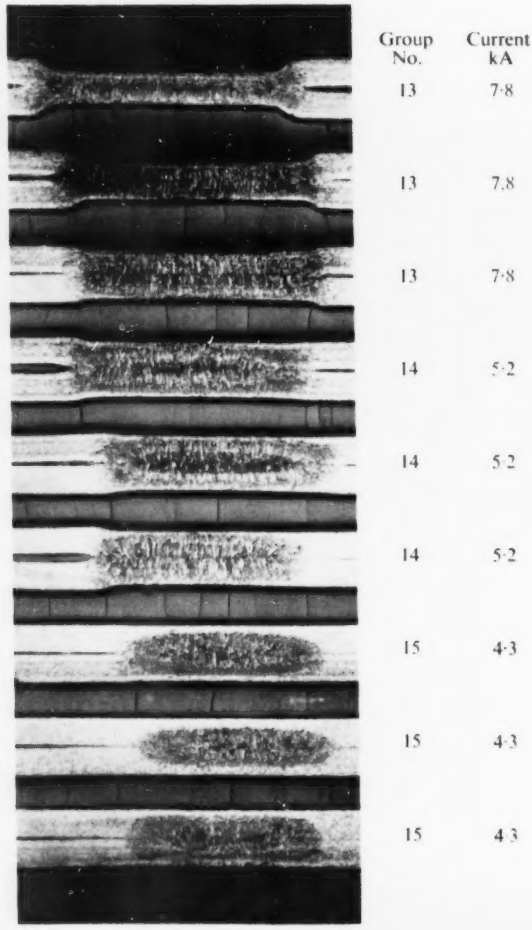

Fig. 4. $\frac{5}{32}$ in. diameter electrode tip—190 lb. load.

The results obtained for 24 s.w.g. material show that:

(1) Welds of satisfactory strength, strength consistency and appearance show nugget penetrations from 40-55 per cent., i.e. appreciably less than the limits 60-80 per cent. suggested in T.21.

(2) Excellent consistency can be obtained for nugget diameters of 80-90 per cent. of the electrode tip diameter. In the extreme case it is possible to produce good welds in which the fused zone is absent, i.e. solid-phase welds, however the consistent formation of such welds requires extremely good surface conditions. It is therefore suggested that spot weld dimensions in 24 s.w.g. sheet should conform to the values given in Fig. 2 (*b*).

Specimen macrographs of the weld sections from the main series are shown in Figs. 3 and 4 for welds made with $\frac{1}{8}$ in. electrodes (120 lb. tip load) and $\frac{5}{32}$ in. electrodes (190 lb. load) respectively.

Optimum Conditions

The conditions given in Table III have been selected on the basis of the requirements given above. It appears that little is to be gained by increasing the current duration beyond five cycles, but since this is often the minimum duration of a machine's timer, and therefore would allow no latitude for lower timing, a longer time of 8 cycles has been recommended. A further series of welds was made, using this time. Similarly, tests were made using times of less than 5 cycles to determine how much the current had to be increased at these shorter times in order to maintain weld strength, and at what point splashing occurred. In these series, specimens were welded for both shear and tension testing, the results are given in Table IV.

These results indicate that strength is maintained at 4 cycles, but below this the current must be increased. At 2 cycles some splashing occurs, and at 1 cycle the weld strength cannot be maintained owing to excessive splashing. It should be noted that if weld times of this order are required, increased tip pressures are necessary to eliminate weld splashing.

The recommended time of 8 cycles gives excellent results, as was anticipated from the previous test series. Typical sections of welds made under the recommended conditions are shown in Fig. 5.

LIFE TESTS ON OPTIMUM CONDITIONS

Procedure

Confirmatory tests on the practical suitability of the conditions recommended in Table IV have been undertaken to determine the weld strength and consistency obtainable after making a known number of welds. More than 2,000 welds were made under each of the three conditions, and 12 single weld test pieces were prepared at pre-determined intervals during the run. The speed of welding throughout the tests was 40 welds per minute (except during the preparation of control test pieces) and the cooling water was controlled at approximately 0·75 gallons per minute. Two welds out of each group were reserved for metallographic examination if required, but sections were only prepared of welds made at the start, and after 500, 1,000, 1,500 and 2,000 welds. These sections showed no deterioration in weld structure or appearance. The electrodes showed no appreciable wear at the end of this period.

Results

The results in Table V show that weld strength and consistency are maintained throughout the 2,000 welds for both electrodes, with a slight tendency for weld strengths to increase towards the end of the test.

CONCLUSIONS

1. Excellent welds can be made in 24 s.w.g. sheet, using a variety of conditions, with strengths of 480-550 lb. shear and coefficients of variation from 2 to 6. The main criteria for the assessment of weld quality are mean shear strength, shear strength consistency, surface indentation and sheet separation.

2. Such welds show weld nugget penetrations of 40-55 per cent. of the sheet thickness, and nugget diameters of 80-90 per cent. of the electrode tip diameter Fig. 2 (*b*).

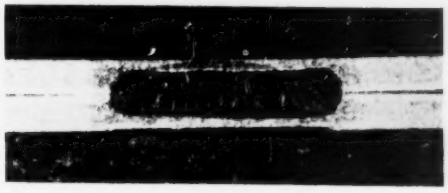

Fig. 5 (*a*). $\frac{1}{8}$ in. dia. electrode tip—120 lb. load, 4·2 kA for 8 cycles.

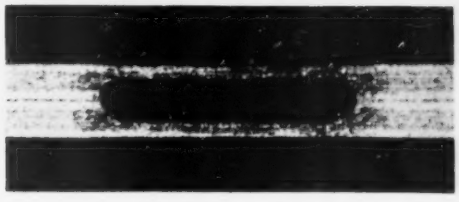

Fig. 5 (*b*). $\frac{5}{32}$ in. diameter electrode tip—190 lb. load, 5·2 kA for 8 cycles.

Table III.—Optimum Welding Conditions (selected from Table II)

Group No.	Electrode Tip Diameter (in.)	Electrode Load (lbs.)	Welding Current (kA)	Weld Time (Cycles 50 c/s)	Mean Strength (lbs.)	Mode of Failure	Coefficient of Variation
8	$\frac{1}{8}$	120 (10,000 lb. per sq. in.)	4·2	5	480	TS	4·2
				10	490	TS-SF	3·7
				15	495	PS	2·4
14	$\frac{5}{32}$	190 (10,000 lb. per sq. in.)	5·2	5	530	PS-TS	1·5
				10	550	SF	1·6
				15	540	SF	2·7

SF = Failure of sheet remote from weld usually near grips.
TS = V-failure of sheet from edge of weld to both edges of strip.
TS-SF = Some specimens TS and some SF failure.
PS = Pulled slug.
PS-TS = Some specimens PS and some TS failure.

3. A weld time of 5 cycles is quite sufficient to produce these welds, but to allow for possible timer inaccuracies a minimum time setting of 8 cycles is recommended. This gives equally good strengths and consistencies as are obtained with 5 cycles.

4. An increase of weld time beyond 8 cycles, up to 15 cycles, gives no advantage in either strength or consistency of results. A limited number of tests beyond 15 cycles showed no falling-off of strength or consistency.

5. No advantages are shown by the use of tip pressures greater than 10,000 lb. per sq. in.

6. Two suggested welding conditions are:

$\frac{1}{8}$ in. tip dia. electrodes 120 lb. load 4·2 kA for 8 cycles
$\frac{5}{32}$ " " " " 190 " " 5·2 " " 8 "

7. The quality of welds made under these conditions is still maintained at the end of a run of 2,000 welds.

Table IV.—Effect of Variations of Current Duration on Current Required to Maintain Weld Strengths

Electrode Tip Diameter (in.)	Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles 50 c/s)	Weld Strengths				
				Shear (lb.)	Coefficient of Variation	Tension (lb.)	Coefficient of Variation	Ratio: $\frac{\text{Tension}}{\text{Shear}}$ (per cent.)
$\frac{1}{8}$	120 (10,000 lb. per sq. in.)	6·0*	1	475	2·8	264	8·7	56
		4·8	2	486	2·7	246	8·4	51
		4·9	3	513	2·1	327	10·2	61
		4·3	4	511	1·9	309	9·0	60
		4·2	5	480	4·2	—	—	—
		4·1†	8	506	3·7	264	9·6	57
$\frac{5}{32}$	190 (10,000 lb. per sq. in.)	7·3*	1	486	2·3	250	5·5	58
		6·6	2	517	2·2	293	4·9	57
		6·4‡	5	573	4·8	448	15·9	59
		5·6†	8	540	2·7	302	5·3	56

* Excessive splashing.
† Recommended conditions.
‡ Current too high.

Table V.—Life Tests on Optimum Conditions

Electrode Tip Diameter (in.)	Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles 50 c/s)	No. of Welds before Testing	Mean Shear Strength (lb.)	Standard Deviation	Coefficient of Variation
$\frac{1}{8}$	120	4·2	8	0	520	13·4	2·6
				100	615	19·4	3·8
				200	535	17·3	3·2
				300	514	16·9	3·3
				400	501	17·2	3·4
				500	518	19·8	3·8
				750	528	4·0	0·8
				1000	533	15·2	2·8
				1250	523	17·0	3·3
				1500	544	10·3	1·9
				2000	555	12·8	2·3
$\frac{5}{32}$	190	4·7	8	0	540	15·7	2·9
				100	540	22·7	4·2
				200	559	17·7	3·2
				300	554	11·4	2·1
				400	485	29·0	6·0
				500	556	7·8	1·4
				600	558	13·9	2·5
				850	571	16·3	2·9
				1100	566	10·0	1·8
				1350	569	17·5	3·1
				1600	574	21·7	3·9
				2000	565	22·5	4·0

Part II.—Spot Welding of $\frac{1}{8}$ in. Thick Low-Carbon Steel

SYNOPSIS

Tests are described on the spot welding of $\frac{1}{8}$ in. steel plate employing $\frac{11}{32}$ in. tip dia. truncated cone electrodes of 30 deg., 20 deg., 10 deg. and 5 deg. face angle, with tip pressures of 10,000, 15,000, 20,000 and 25,000 lb. per sq. in.

These tests confirmed that welds of satisfactory strength and consistency may be made over a wide range of conditions with 30 deg., 20 deg., 10 deg. and 5 deg. face angle electrodes, and the selection of optimum conditions must take account of surface appearance, weld soundness and sheet separation.

In general, tip pressures of not less than 15,000 lb. per sq. in. are required with 30 deg. and 20 deg. face angle electrodes. Some porosity is given with electrodes of 10 deg. and 5 deg. face angle under these conditions, but the welds are otherwise satisfactory and have good surface appearances.

INTRODUCTION

The available literature on the spot welding of $\frac{1}{8}$ in. thick mild steel shows a marked difference in the welding conditions recommended by the various investigators, particularly with regard to electrode contours and electrode tip pressure. It was considered that additional work was required to confirm the suitability or otherwise of such conditions.[3-6]

Table VI gives details of recommended conditions taken from the literature and indicates the wide range of electrode shape, electrode load and welding current which have been used and the results obtained. Truncated cone electrodes are generally favoured, with face angles of 30 deg., 20 deg. and 4 deg. Tip sizes also show a wide variation from $\frac{7}{32}$ to $\frac{1}{2}$ in., although these extreme values are generally not practicable. Tip loads vary within the limits of 500 to 2,000 lb.

A programme of work was prepared using truncated cone electrodes of various face angles and over a range of electrode tip loads.

The object of the tests was to determine welding conditions which would consistently produce welds of satisfactory strength without excessive indentation or splashing, and to determine the adjustment necessary to maintain weld strength and consistency as weld pitch decreases.

The work was carried out in three stages: (1) *Preliminary Tests*—to ascertain general effect of welding conditions on weld quality; (2) *Investigation of Suitable Conditions*—suggested by work covered by item (1); (3) *Tests on Effect of Weld Pitch.*

MATERIALS AND SPECIMEN SIZE

The material used was a balanced steel, supplied in the form of bright drawn flats 2 in. × $\frac{1}{8}$ in., in the finally bright normalised condition, of composition as follows:

Carbon	0·145 per cent.
Silicon	0·055 ,,
Manganese	0·56 ,,
Sulphur	0·049 ,,
Phosphorus	0·038 ,,

The mechanical properties being:

Tensile strength	26·8 tons per sq. in. (60,000 lbs. per sq. in.)
Elongation	33 per cent. on 2 in.
Hardness	124 V.P.N. (10 kilo. load)

Table VI.—Conditions Recommended in the Literature for the Spot Welding of $\frac{1}{8}$ in. Thick Mild Steel

Author and Reference	Electrodes (Truncated Cone)		Minimum Electrode Load (lb.)	Current (amps.)	Weld Time (Cycles 50 c/s)	Breaking Load (lb.)	Nuggets Dia. (in.)	Remarks
	Face Taper (degs.)	Tip Dia. (in.)						
B.W.R.A.[3]	30	$\frac{11}{32}$	1000	14,000	32	..	..	Load based on pressure of not less than 10,000 lb. per sq. in.
Riley[5]	20	$\frac{3}{8}$	1800	17,500	25	6,900	0·40	Hot rolled low C steel pickled and lightly oiled. 42,000-45,000 lb. per sq. in. ultimate strength
			1140	12,900	50	6,500	0·39	
			570	10,000	65	6,150	0·37	
Heuschkel[6]	4	$\frac{5}{16}$	1500	14,600	32 (single weld)	4,600	0·375	Steel of ultimate strength of 45,000 to 55,000 lb. per sq. in.
					50 (at minimum spacing)	5,600	0·375	
Dearden & O'Neill[4]	30	$\frac{7}{32}$	500	9,000	2	4,500-5,600	.. ..	0·18 per cent. balanced steel ultimate strength 58,000 to 61,000.
	30	$\frac{11}{32}$	1000	18,000	1	6,700-7,850		Time column for Dearden and O'Neill gives number of current pulses of thirty cycles "on" and one cycle " off "
				15,000	2			
				13,000	3			
				12,000	4			
				10,000	8			
	30	$\frac{1}{2}$	2000	24,000	1	9,000-11,000		
				20,000	3			
				16,000	8			
				13,000	16			

The surface of the material was free from rust or scale and no surface preparation, other than degreasing, was required. The specimens for the preliminary tests were 12 in. lengths, fully overlapped, with six welds made at 2 in. pitch, the first being 1 in. from one end. For the main series, 6 in. lengths were used, overlapped 2 in., and a single weld made at the centre of the overlap.

WELDING MACHINE AND EQUIPMENT

The welding machine used in these tests was a 100 kVA projection welder, fitted with spot welding electrode holders mounted in the centre of the platen. The current control was by means of a thyratron timer and ignitron contactors. Initiation of the weld was governed by a pressure switch, set to operate when the welding load was reached.

Secondary current was measured during welding by means of an air-cored toroid linking with the secondary circuit of the machine, the output of the toroid being integrated and fed to a cathode ray oscillograph and photographed.

Standard 1 in. diameter electrodes, of copper-chromium alloy, were used throughout.

TESTING PROCEDURE

The specimens from the preliminary series were examined by sectioning and etching the welds, and measuring the diameter of the fused zones produced. This method was adopted in preference to shear testing so as to conserve material.

The specimens of the main series were tested in shear, using a 30-ton tensile testing machine on the 6-ton range. Small pads of material were welded on each end before testing, to minimise distortion under loading so that the stress in the weld would be mainly shear. Welds from each condition of the main series were also sectioned, polished and etched, for measurement of weld diameter, penetration and indentation.

PRELIMINARY SERIES

Electrodes with a constant tip diameter of $\frac{11}{32}$ in. (approximately $d = \sqrt{t}$) and face angles of 5 deg., 10 deg., 20 deg. and 30 deg. were used.

For the 30 deg. and 20 deg. face angles, loads based on tip pressures of 10,000, 15,000 and 20,000 lb. per sq. in. and for 10 deg. and 5 deg., tip pressures of 15,000, 20,000 and 25,000 lb. per sq. in. were used.

For each combination of electrode face angle and load, a series of six welds was made in a 12 in. long specimen at 2 in. pitch, with the same current setting and increasing time. A pitch of 2 in. was used since this was large enough to enable any effects of current shunting through previous welds to be neglected, and used considerably less material than individual specimens would have done. This was repeated over a range of current, five values being used. The limits of the ranges of current and time were fixed by the requirements that—

(i) at the high current end of the range, excessive indentation and splashing should be avoided;

(ii) at the low end of the current range, times of 150 cycles or less should produce a weld of satisfactory size.

Similar considerations governed the time range used, i.e. the short times must produce a weld of suitable size, and the long times must not produce excessive indentation or splashing. The range of current was from 8,500 amps. to 26,000 amps. with times from 5 to 150 cycles to suit the particular current in use.

All welds were sectioned and their diameters measured and plotted against time for the various current magnitudes to give "characteristic curves," examples of which are shown in Figs. 6-17.

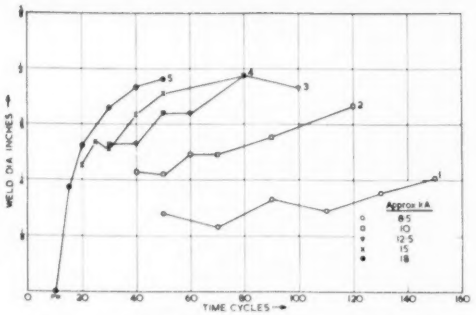

Fig. 6. Electrode tip diameter $\frac{11}{32}$ in.—load 925 lb.—face angle 30 deg.

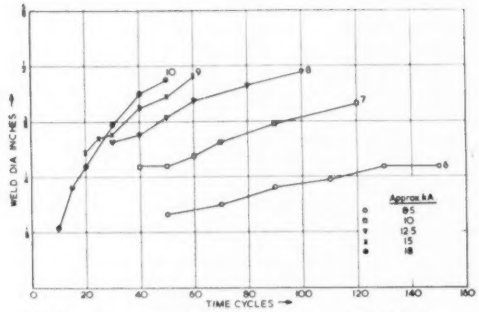

Fig. 7. Electrode tip diameter $\frac{11}{32}$ in.—load 925 lb.—face angle 20 deg.

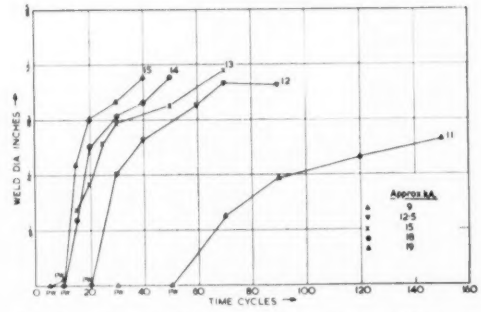

Fig. 8. Electrode tip diameter $\frac{11}{32}$ in.—load 1400 lb.—face angle 30 deg.

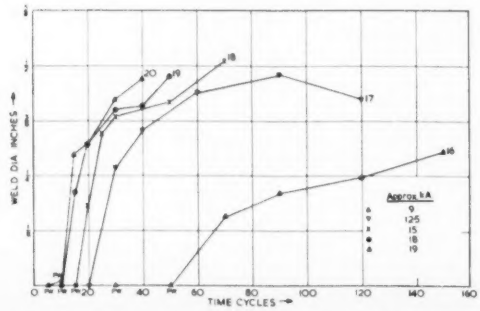

Fig. 9. Electrode tip diameter $\frac{11}{32}$ in.—load 1400 lb.—face angle 20 deg.

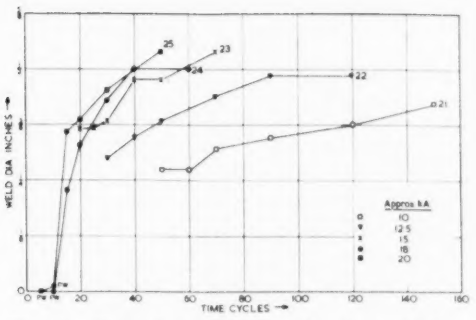

Fig. 10. Electrode tip diameter $\frac{11}{32}$ in.—load 1400 lb.—face angle 10 deg.

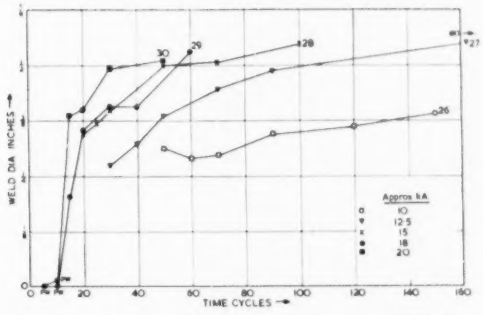

Fig. 11. Electrode tip diameter $\frac{11}{32}$ in.—load 1400 lb.—face angle 5 deg.

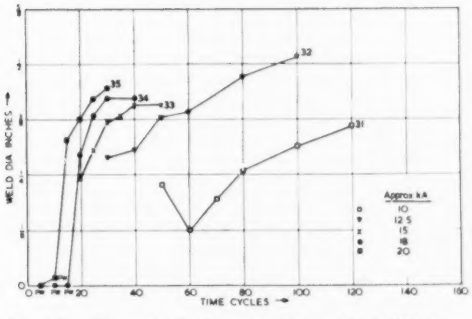

Fig. 12. Electrode tip diameter $\frac{11}{32}$ in.—load 1850 lb.—face angle 30 deg.

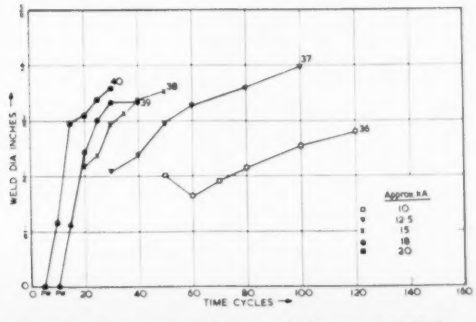

Fig. 13. Electrode tip diameter $\frac{11}{32}$ in.—load 1850 lb.—face angle 20 deg.

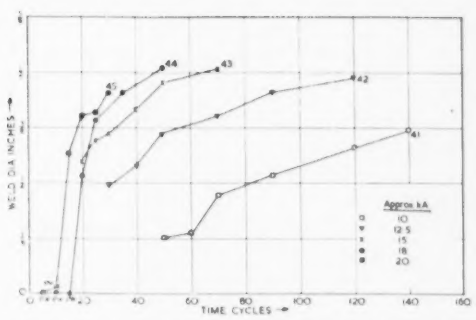

Fig. 14. Electrode tip diameter $\frac{11}{32}$ in.—load 1850 lb.—face angle 10 deg.

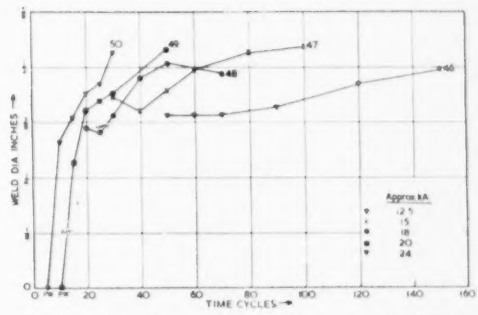

Fig. 15. Electrode tip diameter $\frac{11}{32}$ in.—load 1850 lb.—face angle 5 deg.

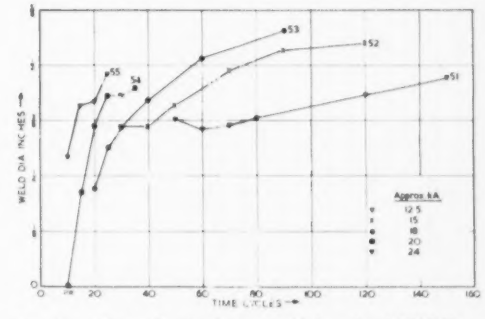

Fig. 16. Electrode tip diameter $\frac{11}{32}$ in.—load 2325 lb.—face angle 10 deg.

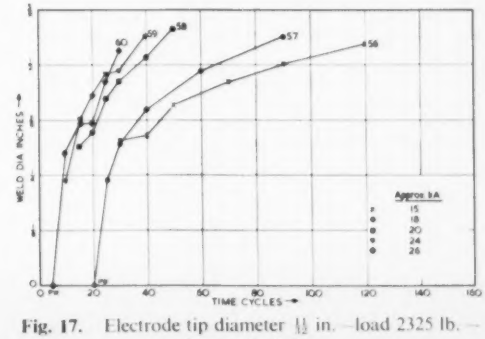

Fig. 17. Electrode tip diameter $\frac{11}{32}$ in.—load 2325 lb.—face angle 5 deg.

These curves, together with visual examination of the sections, and the surface appearance of the specimen, were used to select conditions worthy of further investigation. The initial assumption was that the weld diameter should be equal to, or greater than, the electrode diameter, but without excessive penetration resulting in surface burning, and also without heavy indentation or splashing.

MAIN SERIES

Welding Conditions

Conditions were selected as described in the preceding section, and for each electrode face angle and load condition three currents were used, usually the highest, middle and lowest of those used in the preliminary series. The current duration was selected in accordance with the current magnitude to produce a suitably sized weld.

For each of these conditions twelve specimens were welded of which ten were tested in shear and the remaining two kept for sectioning.

Examination of Results

The welding conditions for the main series of tests, together with average strength and coefficient of variation, are given in Table VII.

From this table it is easily seen that the consistency of strength for all the conditions used is very good indeed. Only two of the coefficients of variation exceed 5 per cent., and many are less than 2 per cent. The average strength is also quite adequate, being between 3 and 4 tons for all conditions. The majority of the failures were by shear of the weld. This excellence over the wide range of conditions used makes the selection of the "best" conditions difficult, and it is only by being extremely critical that any can be eliminated.

A number of the conditions used gave rise to slight splashing as marked in Table VII, though this was never of a serious nature. However, as it is desirable to avoid splashing entirely, these conditions may be eliminated. Any further selection has to be based on weld appearance, both of the surface and the weld section rather than mechanical properties. Representative sections of welds from each condition are shown in Figs. 18-23. The general conclusions from such an examination are:

1. 10,000 lb. per sq. in. tip pressure with 30 deg. and 20 deg. face angle electrodes is not to be recommended as it is liable to allow splashing before a weld of adequate size is formed, and to give uneven heat distribution.
2. 15,000 lb. per sq. in. tip pressure with 30 deg. or 20 deg. electrodes gives reasonable results, a medium current/medium time condition being best, provided a fair indentation can be tolerated (5-10 per cent.). A higher current may be used, with shorter time and less indentation, but slight splashing may result. For 10 deg. and 5 deg. face angles the load is rather low, and considerable porosity can occur. The low currents here need such long times to produce a weld of suitable size that carbon migrates to the centre of the weld, leaving a shell of ferrite at the edge of the fused nugget, see Figs. 21 (Group 19) and 22 (Group 28), while higher currents tend to result in splashing.

Table VII.—Test Data for $\frac{1}{8}$ in. Steel Spot Welds

Electrode Face Angle (degs.)	Elec. Load (lb.)	Welding Current (kA)	Weld Time (Cycles 50 c/s)	Mean Shear Strength (tons)	Coefficient of Variation	Mode of Failure	Remarks
30	925	10·1	90	3·43	2·6	Shear	
		—	30	3·38	2·8	,,	Splash
		14·8	20	3·22	3·8		,,
	1400	9·5	100	3·02	6·4		
		13·3	30	3·06	2·7		
		15·3	20	3·34	4·2		
	1850	10·3	120	3·23	0·9	,,	
		13·7	30	3·26	2·0		
		14·7	15	3·03	6·5		
20	925	10·4	90	3·45	2·6		
		14·4	40	3·51	2·7		,,
		13·7	20	3·31	2·1	,,	,,
	1400	9·6	100	3·06	3·6		
		13·3	40	3·40	2·2		Slight splash
		15·2	20	3·32	4·2		
	1850	—	100	3·17	1·7	,,	
		14·6	40	3·43	2·7		
		15·4	20	3·39	4·7		
10	1400	10·6	120	3·45	1·9		
		14·4	30	3·56	2·1	,,	Splash
		18·7	15	3·46	3·5		,,
	1850	12·6	70	3·54	1·0		
		14·3	40	3·54	2·0	,,	
		18·8	15	3·49	2·8	Pulled slug	,,
	2325	13·3	80	3·58	1·3	Shear	
		16·7	40	3·92	4·1	,,	
		21·0	15	3·71	1·1	Pulled slug	,,
5	1400	9·6	120	3·28	1·9	Shear	
		12·8	30	3·56	2·9	,,	
		18·3	15	3·43	3·7	,,	Slight splash
	1850	12·6	70	3·60	1·8	,,	
		15·8	30	3·64	1·6	,,	
		22·1	10	3·55	1·0	Pulled slug	
	2325	15·0	50	3·64	1·4	Shear	
		18·7	30	4·18	3·2	Pulled slug	Occasional splash
		22·3	15	3·76	2·7	Shear	,,

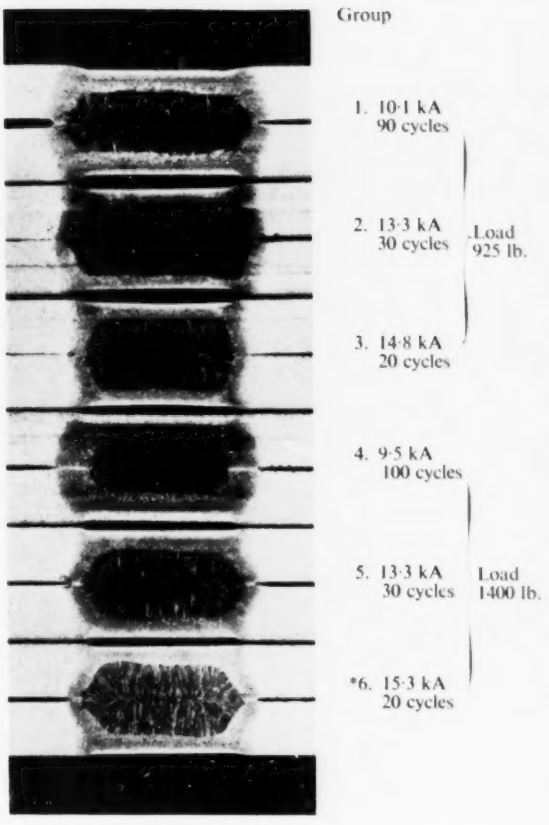

Fig. 18. Face angle 30 deg.

* *Weld made using recommended condition.*

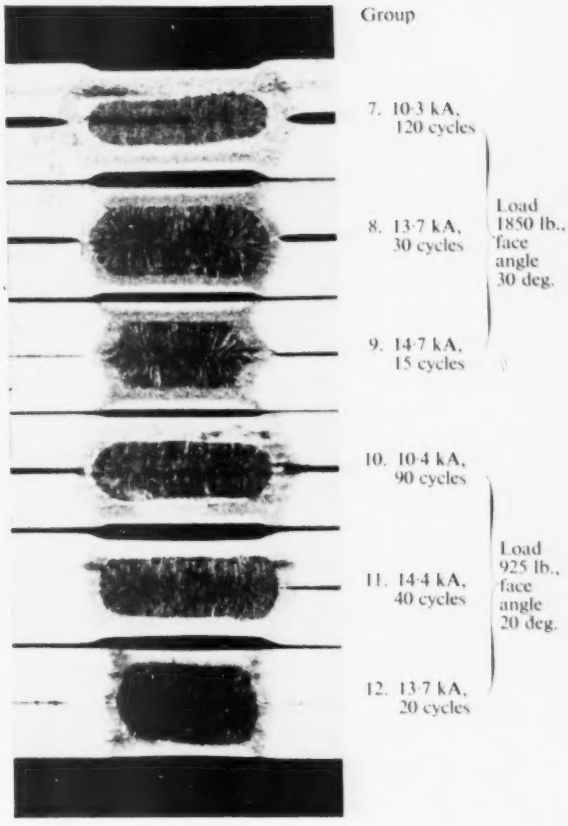

Fig. 19.

3. 20,000 lb. per sq. in. tip pressure with 30 deg. and 20 deg. electrode gives a fair amount of sheet separation; the top and medium currents both give reasonable results, with rather greater indentation in the case of the medium current. With 10 deg. and 5 deg. face angles, good sound welds can be made using medium currents, without excessive indentation.
4. 25,000 lb. per sq. in. with 10 deg. and 5 deg. face angles. At this the indentation is heavy under all conditions and the energy consumption is high. Occasional splashing can occur with the highest current, and the welds still contain some porosity although higher strengths may be obtained.

Keeping these facts in mind, the conditions given in Table VIII have been selected as the optimum of those investigated. Conditions have been included for each electrode face angle. Examination of Table VIII shows reasonable welds can be made for $\frac{11}{32}$ in. electrodes with face angles of 30 deg., 20 deg., 10 deg. and 5 deg. with a minimum tip pressure of 15,000 lb. per sq. in., a welding current from 15,000 to 16,000 amps. r.m.s., and weld time from 20-30 cycles. The welds made under these conditions with varying electrode face angles show some variations in strength and general features, but are generally satisfactory.

Tests on Effect of Weld Pitch

Tests using the selected conditions were made with weld

Table VIII.—Some Satisfactory Welding Conditions for $\frac{1}{8}$ in. Steel Plate

Group No.	Electrode Face Angle (degs.) for $\frac{11}{32}$ in. Tip Dia.	Electrode Tip Pressure (lb. per sq. in.)	Elec. Load (lb.)	Measured Mean Welding Current (kA)	Weld Time (Cycles 50 c/s)	Mean Shear Strength (tons)	Coefficient of Variation	Surface Indentation (approx.) (per cent.)
6	30 deg.	15,000	1400	15·3	20	3·34	4·2	5-7
15	20 ,,	15,000	1400	15·2	20	3·32	4·2	5-7
18	20 ,,	20,000	1850	15·4	20	3·39	4·7	10
23	10 ,,	20,000	1850	14·3	40	3·54	2·0	10
29	5 ,,	15,000	1400	12·8	30	3·56	2·9	5
32	5 ,,	20,000	1850	15·8	30	3·64	1·6	5

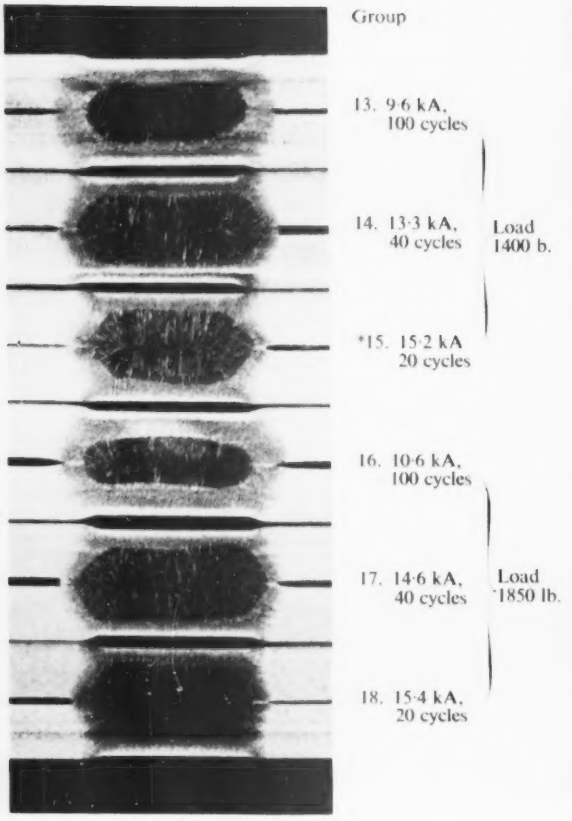
Group
13. 9·6 kA, 100 cycles
14. 13·3 kA, 40 cycles
Load 1400 b.
*15. 15·2 kA 20 cycles
16. 10·6 kA, 100 cycles
17. 14·6 kA, 40 cycles
Load 1850 lb.
18. 15·4 kA, 20 cycles

Fig. 20. Face angle 20 deg.

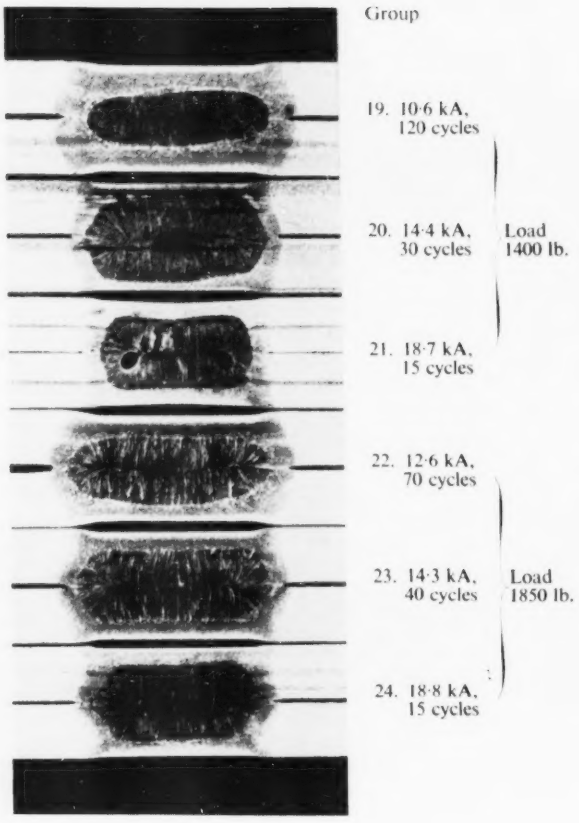
Group
19. 10·6 kA, 120 cycles
20. 14·4 kA, 30 cycles
Load 1400 lb.
21. 18·7 kA, 15 cycles
22. 12·6 kA, 70 cycles
23. 14·3 kA, 40 cycles
Load 1850 lb.
24. 18·8 kA, 15 cycles

Fig. 21. Face angle 10 deg.

* *Weld made using recommended conditions.*

pitches of 1½, 2 and 3 times the electrode tip diameter. The results indicated a fall in strength, most noticeable with high-current/short time conditions, which an increase in current could not counteract as excessive splashing resulted from such an increase. An increase in time from 20 to 25 cycles, with no increase in current (using 15kA), allowed weld strength to be maintained at a pitch of 3d. At smaller pitches difficulties arise from surface splashing. Strength can be maintained at 2d by increasing time to 30 cycles, but the conditions are not recommended.

CONCLUSIONS

Welds of satisfactory shear strength (3·0-3·75 tons) and consistency and good appearance can be made with electrodes of 30 deg., 20 deg., 10 deg. and 5 deg. face angle. An electrode tip pressure of not less than 15,000 lb. per sq. in. is required with 30 deg. and 20 deg. electrodes to ensure uniform heating. Generally, the appearance of welds made with the 10 deg. and 5 deg. face angle electrodes is to be preferred, but tip pressures of about 20,000 lb. per sq. in. are required to reduce porosity. For the tests described, the mean weld strength with 10 deg. and 5 deg. electrodes is within the range of 3½-4 tons, and with 30 deg. and 20 deg. electrodes, 3-3½ tons. As weld pitch is reduced, an increase of time can be used to maintain the strength of the second and subsequent welds, though weld pitches of less than 3 × electrode tip diameter are not recommended.

It is possible that a more discriminating test of the conditions would be given by extended consistency runs involving several hundred welds, but unfortunately this has not been possible because of lack of material. In general, the results obtained are a confirmation of the relatively wide range of conditions recommended in the literature for spot welding ⅛ in. thick material. The selection of a particular condition as a "practical optimum" is a matter of difficulty and will have to take account of the practical conditions existing and the particular weld requirements.

For general serviceability, i.e. production of sound welds of good appearance and ease of location of parts under the electrodes, a 20 deg. face angle is recommended. Using a tip pressure of 15,000 lb. per sq. in. (1,400 lb. total load on $\frac{11}{32}$ in. diameter tip) and a current of 15kA for 20 cycles sound welds have been produced. Using a tip pressure of 10,000 lb. per sq. in., uneven heating and irregular weld shapes may be produced, but strength and consistency are generally good. A 30 deg. face angle may be used with the same welding conditions, if desired, though weld appearance will suffer and electrode life will probably decrease. Macrographs of welds made under these two conditions are given in Fig. 18, Group 6, and Fig. 20, Group 15.

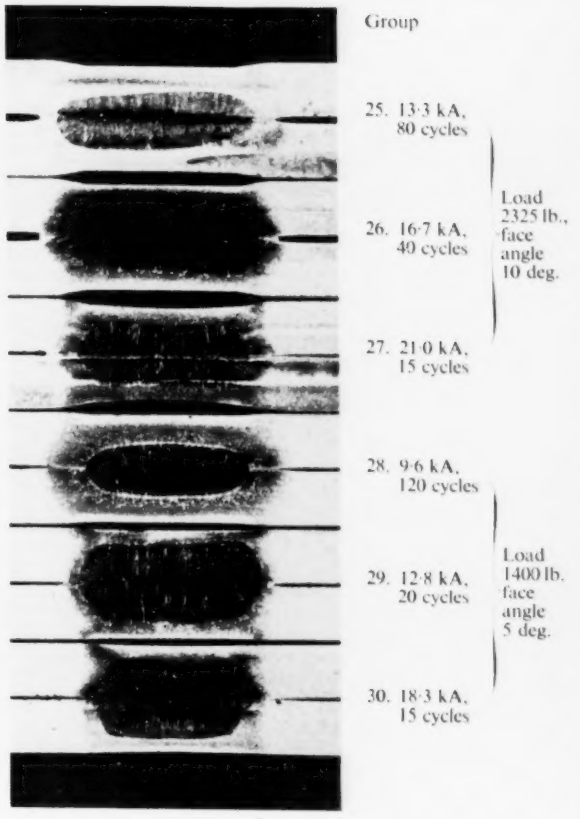
Group
25. 13·3 kA, 80 cycles
26. 16·7 kA, 40 cycles
27. 21·0 kA, 15 cycles
28. 9·6 kA, 120 cycles
29. 12·8 kA, 20 cycles
30. 18·3 kA, 15 cycles
Load 2325 lb., face angle 10 deg.
Load 1400 lb. face angle 5 deg.

Fig. 22.

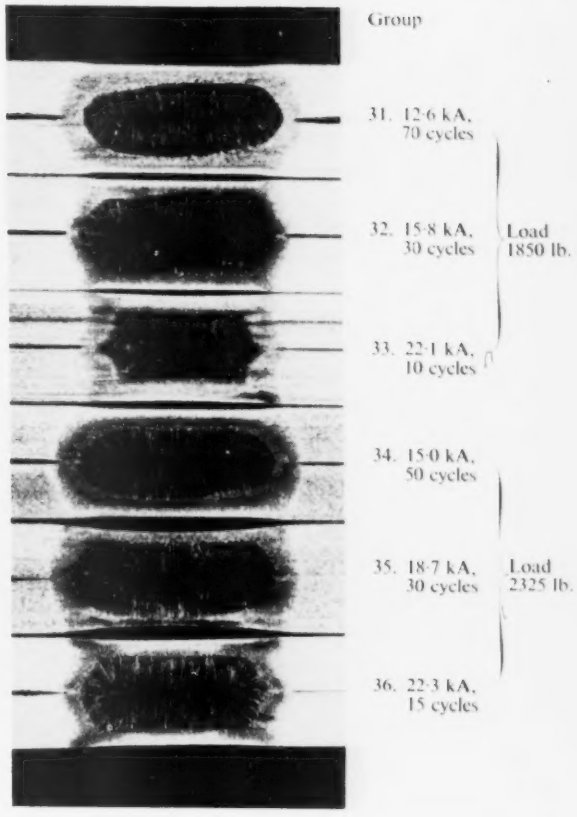
Group
31. 12·6 kA, 70 cycles
32. 15·8 kA, 30 cycles
33. 22·1 kA, 10 cycles
34. 15·0 kA, 50 cycles
35. 18·7 kA, 30 cycles
36. 22·3 kA, 15 cycles
Load 1850 lb.
Load 2325 lb.

Fig. 23. Face angle 5 deg.

ACKNOWLEDGMENTS

The investigators would like to thank Mr. C. L. Railton, of Tube Investments (Group Services) Ltd. for the use of a welding machine for the short-time tests for the welding of 24 s.w.g. steel and for help during these tests.

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THE MEASUREMENT OF SPOT WELDING MACHINE VARIABLES

This is the second report on a programme of work on the spot welding of aluminium alloys carried out by the B.W.R.A. on behalf of the Ministry of Supply. The report describes methods developed for the control of condenser discharge machines although the methods are applicable to other types of resistance welding equipment. Appendix I of the report, on the cathode follower integrator, was prepared by R. B. Chitty.

The work described in this report was first issued to Members of the Association in 1950/51 (*Reports LR9/A and LR/17*). *The first report on the programme of work* (*LR/8A*) *was published in the October*, 1952, *issue of WELDING RESEARCH.*

By H. E. Dixon, M.Sc., A.I.M., J. E. Roberts, M.Eng., A.I.M., and T. M. Roberts.

SYNOPSIS

Methods adopted for the measurement of secondary current and voltage, electrode load cycle and tip velocity and condenser charging voltage are described. Improvements in the air-cored toroid and integrating circuit method of current measurement have been introduced, with replacement of the simple R-C integrator by a cathode follower integrator and the use of direct-coupled amplifiers.

A very simple but efficient deflection unit has been developed for load cycle measurement, using electric resistance strain-gauges, wired in a bridge network with balancing resistance and capacitance. The method of recording is fully described and sections are included on the oscillograph equipment, recording camera and the measurement of records.

The operation of the cathode follower integrator is examined in detail in the Appendix I.

INTRODUCTION

The main research programme on the spot welding of light alloys was the analyses of the factors controlling the formation of welds in light alloy sheets. A primary requirement before commencing the programme was the measurement of the more important machine variables controlling the formation of the weld, i.e. secondary current, electrode load cycle and the electrode tip velocity. Other variables measured, but of less importance, were condenser charging voltage and secondary voltage. It was recognised in the early stages of the investigation that large numbers of records would be required, particularly of secondary current and electrode load cycle, and that this would have to be taken into consideration in assessing the suitability of various methods available.

MEASUREMENT OF INDIVIDUAL VARIABLES

Secondary Current

The method used for secondary current measurement was based on that described by Bennett & Dixon* with several modifications. In this method a specially designed air-cored toroid (Fig. 1) is placed around the top spot welding electrode to link with the secondary current. The output from this coil is electrically integrated and the integrated signal fed into the amplifiers of a suitable oscillograph. The modifications used were as follows:

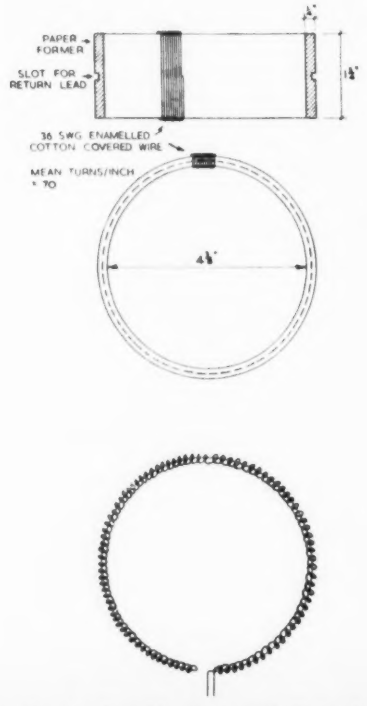


Fig. 1. Layout of toroid and schematic illustration showing return lead.

* *Welding Research*, **2** (2), April, 1948.

Replacement of R-C Integrator by Cathode follower Integrator.—The attenuation of the signal from the toroid by a simple R-C circuit is very great, and when the signal is initially low, considerable amplification must be used, with its associated difficulties, to obtain satisfactory deflection on the C.R.O. It was desirable to use a method which would be satisfactory for small inputs without requiring high amplification, i.e. the integrated signal to be large for small secondary currents. The output voltage V_o across condenser C (Fig. 2) is given by the relation:

$$V_o = \frac{1}{CR}\int V_i dt$$

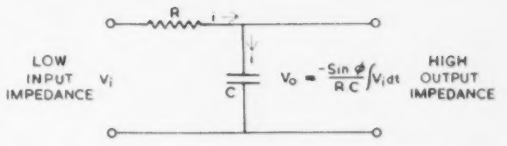
where V_i is the input voltage, hence the output voltage is proportional to the integral of the input voltage. This result is based on the assumption that the voltage across the condenser, i.e. the output voltage, is negligible compared with the input voltage. The need for high amplification prior to oscillograph recording is obvious. In the cathode follower type of integrator this difficulty is overcome by injecting into the input circuit a voltage at all times equal and opposite to the voltage across the condenser. Since the voltage across the condenser is thus cancelled **out,** the output voltage can be quite large compared with that of the input. A simplified circuit diagram of the cathode follower integrator is given in Fig. 3. The triode shown has a very large amplification, i.e. a very small change in the voltage between the grid and the cathode causes a large change in the current through r_c. If the voltage across the condenser C increases, the voltage between the grid and cathode tends to increase so that the current through the valve and r_c will increase. The voltage across r_c increases and will continue to increase until the voltage difference between the cathode and grid is reduced to the small value required to produce the change in current through r_c. The voltage of the cathode thus follows the grid voltage across the condenser. The input circuit is connected so that the voltage across r_c is in opposition to that across the condenser. A description of the practical circuit for a cathode follower integrator is given in the Appendix I together with an analysis of its operation.

Use of Direct Coupled Amplifiers.—It was estimated from previous work that the total current discharge time for one of the condenser discharge machines used for this work would be about 1/10th of a second, and for the other machine about 0·4 to 0·5 seconds. In these circumstances it was decided to use direct coupled amplifiers for current wave measurement of both machines. Some commercially available A.C. amplifiers incorporated in oscillograph equipment are not suitable for current pulses of this duration; however the performance of the Cossor model 1049 oscillograph, the amplifiers of which are direct coupled, was found to be quite satisfactory.

Electrode Load Cycle

A method was required which would not interefere with the normal use of the welding machine and which would be simple and robust. Electric resistance strain-gauges were considered most suitable and the problem was to provide a simple unit which could be incorporated in the top electrode holder. The unit adopted comprised two steel discs of 4-in. diameter, the top disc being deflected during welding by the bottom of the piston shaft operating the top electrode. Electric resistance strain-gauges attached to the top disc measured the varying load during welding by means of the deflection of the disc, which was proportional to the applied load.

The design of the deflection discs is given in Fig. 4 and their location above the electrode platen is shown in photograph (Fig. 5). The top disc is drilled and the drilled holes linked by slots as shown in Fig. 4, in order to adjust the disc deflection in accordance with the maximum load available.



ϕ is phase difference between input and output voltages and is given by $\tan\phi = -\omega CR$ *and if* $\omega CR = 2\pi f_1 CR > 5$ *where f_1 is lowest frequency component, then*

$$90^\circ > \phi > 78{\cdot}5^\circ$$

or

$$1 > \sin\phi > 0{\cdot}981$$

and

$$V_o \doteq \frac{1}{CR}\int V_i dt$$

With an error of less than 2 per cent.

Fig. 2. Resistance capacitance integrator.

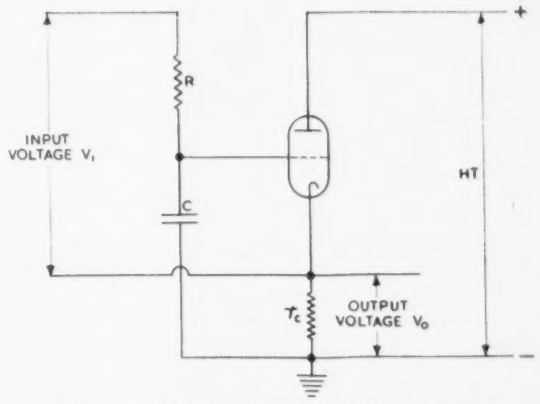


Fig. 3. Simplified circuit of cathode follower integrator.

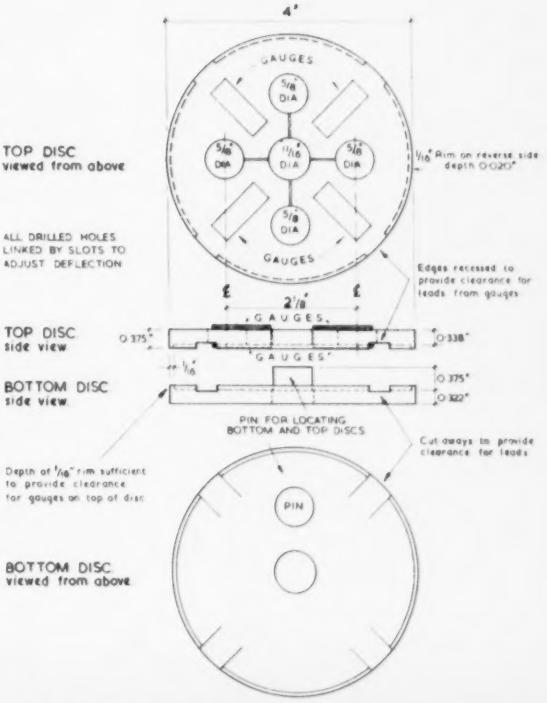
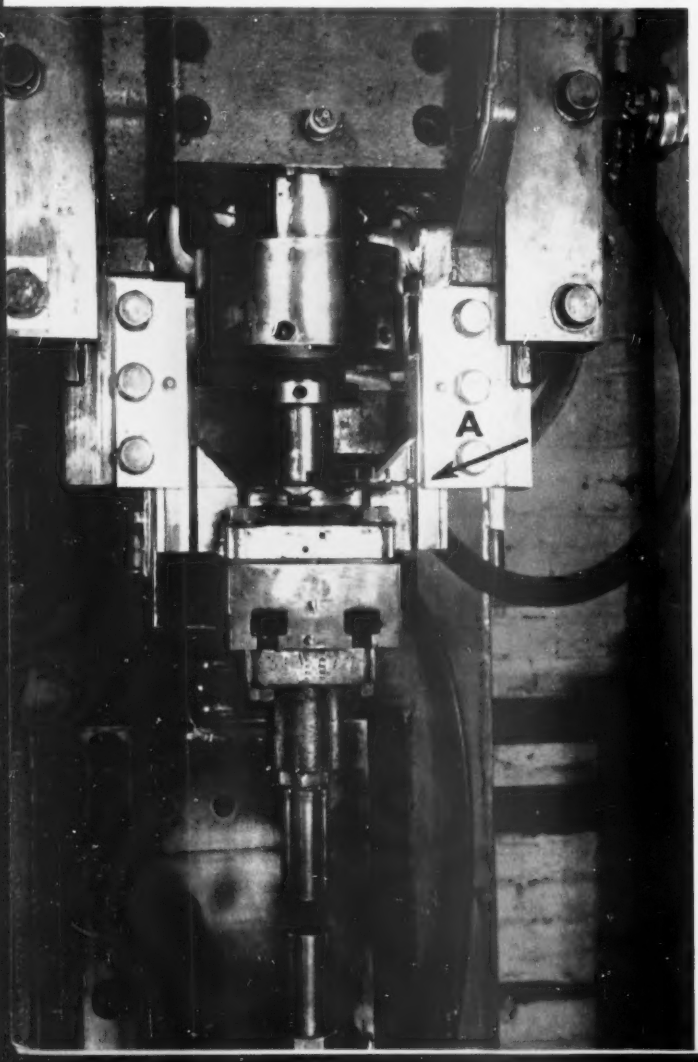


Fig. 4. Deflection discs for load measuring unit (dimension for maximum tip load of 2,500 lbs.).

Four strain gauges are symmetrically disposed on the top surface of this disc and four on the bottom surface. These gauges are wired in a Wheatstone Bridge network, so that each arm of the bridge contains two like gauges (i.e. gauges either in tension or compression) and adjacent arms comprise unlike gauges (Fig. 6).

One pair of gauges is shunted with a variable resistor and another pair with a variable condenser for initial balancing of the bridge, i.e. where no load is applied. The input to the bridge is from a 1,000 c/s oscillator and the output is taken to a 30 : 1 line transformer and thence to the oscillograph. The position of this transformer is important with regard to the welding machine and oscillograph equipment. It was found that inductive pick-up in the windings of the line transformer due to the magnetic field from the secondary loop of the welding machine could be eliminated by placing the transformer (which is of the shell type) at the same height as the centre of the secondary loop and with the axis of its coils vertical. The transformer must also be remote from the oscillograph to reduce 50 c/s pick-up. The selection of the bridge arms for the balancing resistor and condenser is by trial and error, and when the bridge is initially balanced any deflection of the disc (when load is applied) will alter the resistance of the gauges and upset the bridge balance. The gauges are strained in tension or compression depending on their position on the deflection disc (top, tension; bottom, compression). The thickness of the disc and the position of the holes ensure that the output of the bridge is linear. The balancing circuit is placed near the oscillograph so that the operator of the recording camera can make any necessary adjustments during welding. It will be noted that all the gauges used are active and that no dummy gauges are necessary. Any alteration in initial balance over a period of time can, of course, be corrected by means of the balancing resistor and condenser. The unit is calibrated by applying a known static load, measured by means of a Statimeter* or specially developed device (Appendix II) and observing the oscillograph deflection produced. This calibration is normally made after every record or group of records, using the same amplifier settings, so that temperature variations affecting gauge sensitivity and amplifier drift are not of importance. Once the bridge has been balanced, only slight alterations in resistance are required from day to day to maintain the bridge balance, and it is rarely necessary to adjust capacitance.

Fig 5 (*below*). Spot welding machine showing location of deflection unit (A) between piston and top electrode platen.



Electrode Tip Velocity

A review of recent literature† did not reveal any information on the effect of electrode tip velocity, although it is conceivable that this variable may affect the formation of a weld. For example, a considerable momentum has to be dissipated on impact, when high tip velocities are used and the breakdown of the surface resistance may be affected by this momentum. It is anticipated, however, that the effect will only be noticeable at very high tip velocities, i.e. it is not expected that the variations in tip velocity normally encountered in practice, will have any important effect. A drawing of the simple instrumentation adopted for this measurement is shown in Fig. 7. In this method the movement of the top electrode platen is used to operate the moving arm of a uniformly wound toroidal potentiometer. An input of 1,000 c/s is fed into the potentiometer, and the output taken from the moving contact and that end of the potentiometer corresponding to zero output. This output is fed into a line transformer (30 : 1 ratio) and thence to the oscillograph. Movement of the top electrode platen causes an adjustable striker to make contact with an anvil fitted to a Bowden cable, which operates the moving potentiometer contact by means of a spindle and simple gearing. As the electrode moves the anvil is carried forward by the striker which thus operates the moving arm on the potentiometer. The design of the unit is such that an electrode movement of 0·233 ± 0·001 in. is equivalent to the maximum circumferential movement of 4·26 in. on the potentiometer. The position of the striker is normally adjusted so that contact with the anvil is just made when the top electrode is about 0·233 in. from the material being welded, so that when the electrode touches the work piece the moving arm is near the limit of its travel. This point corresponds to near maximum amplitude of signal, and the amplitude of the signal at any instance is thus a measure of the space position of the top electrode. The tip velocity at any instant is given by the slope of the distance/time curve which is photographically recorded in the oscillograph. The potentiometer is so wound that, although the rotor arm has complete freedom to move through almost 360 deg., change of signal takes place over the central portion only (approx. 190 deg.). This means that the contact can continue to move above the point corresponding to maximum output signal (closure of electrodes) and such movement will occur when the

* Trade Name.

† Teanby, P. M. "A review of recently published information on the Spot Welding of Light Alloys," *Welding Research*, **4** (5) October, 1950.

bottom electrode arm deflects under the action of increasing tip load.

The Bowden wire is attached to the bottom of the welding machine, and a spring maintains the correct wire tension. A second spring attached to the arm operating the moving contact prevents overshoot of the moving contact and returns the contact to the zero position when the electrodes part at the completion of welding.

Condenser Charging Voltage and Secondary Voltage

For general purposes only secondary current and electrode load cycle are simultaneously recorded and measured, but the need has arisen from time to time for measurement of condenser charging voltage and secondary voltage.

Condenser Charging Voltage.—It is not normally possible to observe the voltage on the condensers during welding because of the inertia of the movement of the meter provided. This meter is quite satisfactory for observing condenser forming voltages when the meter has time to stabilise. During welding higher voltages are obtained for a given rectifier transformer tapping since the resistance incorporated in the circuit during forming is excluded. Normally a welding voltage of about 25 volts in excess of the appropriate forming voltage is obtained. The exact voltage, however, is best determined by means of an oscillograph, and this method also enables the total time available for charging to be assessed accurately. This matter is of importance since any increase in electrode tip velocity might materially affect the condenser charging time and hence the charge on the condensers. Without a knowledge of the charging time and charging voltage, it would be impossible to separate the effect of electrode tip velocity from the effect of charging voltage.

The voltage on the condensers was measured on the input side between the rectifier and the condensers. This avoids difficulties arising from the reversal of direction of discharge into the primary of the welding transformer (by means of reversing contactors). If measurements are taken across the primary of the welding transformer the oscillograph equipment has to be "floated" (i.e. no earth), which is not always desirable. The charging voltage could be fed directly into one amplifier of the oscillograph by selecting a suitable range on the switch provided.

Secondary Voltage.—The voltage drop between the electrodes during welding varies between 0·3 and 0·5 and because of this small magnitude particular care must be taken to reduce unwanted pick-up voltages. It is essential to use screened cable and to have the oscillograph equipment remote from the welding machine. Connections to the electrodes must be kept as close as possible and the leads must be brought out at right angles to the electrode axis and in the plane of the secondary loop of the machine. During the discharge of the welding current the potential of the bottom arm of the machine rises above earth potential, making it absolutely necessary that the recording equipment and bottom arm of the machine should be connected to the same earth. In practice it has been found best to provide one earth only at the oscillograph and to tie the return lead and screening to the bottom electrode and to the common or earth terminal on the oscillograph. Every care must be taken to ensure that pick-up is reduced to an acceptable low figure.

SIMULTANEOUS MEASUREMENT OF ANY TWO VARIABLES

It is possible to measure any two variables simultaneously, employing both beams of the Cossor double beam oscillograph. Two such combinations are described below.

Secondary Current and Electrode Load Cycle

These are the most important variables for simultaneous measurement and a schematic circuit of the instrumentation used is illustrated in Fig. 8.

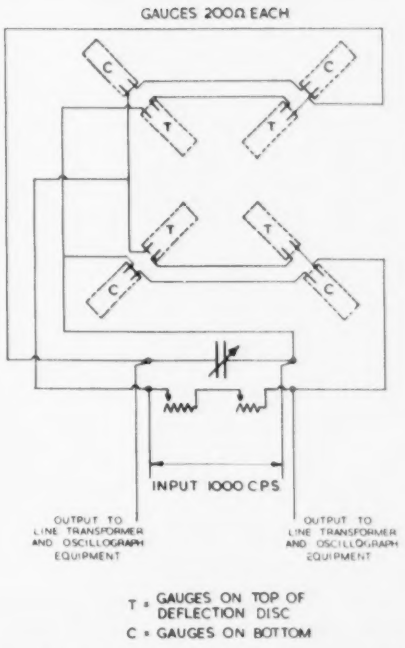
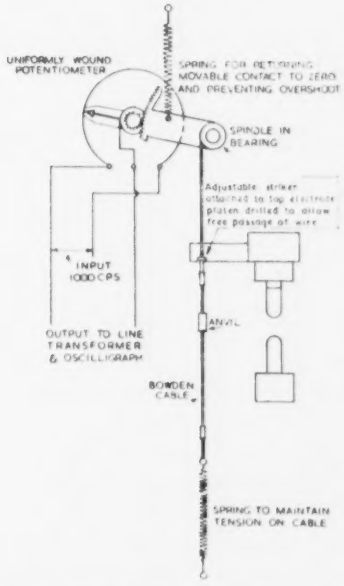

GAUGES 200Ω EACH
C
T
INPUT 1000 CPS
OUTPUT TO LINE TRANSFORMER AND OSCILLOGRAPH EQUIPMENT
OUTPUT TO LINE TRANSFORMER AND OSCILLOGRAPH EQUIPMENT
T = GAUGES ON TOP OF DEFLECTION DISC
C = GAUGES ON BOTTOM

Fig. 6. Bridge network for load measuring unit.


UNIFORMLY WOUND POTENTIOMETER
SPRING FOR RETURNING MOVABLE CONTACT TO ZERO AND PREVENTING OVERSHOOT
SPINDLE IN BEARING
Adjustable striker attached to top electrode platen drilled to allow free passage of wire
INPUT 1000 CPS
OUTPUT TO LINE TRANSFORMER & OSCILLIGRAPH
ANVIL
BOWDEN CABLE
SPRING TO MAINTAIN TENSION ON CABLE

Head movement of 0·233 ± 0·001 *in. is equivalent to maximum circumferential movement of* 4·26 *in. Amplitude of signal is measure of space position of top electrode and tip velocity at any instant is given by slope of distance-time curve.*

Fig. 7. Device for determining electrode tip velocity.

The integrator output is fed into the A.1 amplifier of the Cossor oscilliograph and the output of the line transformer into an auxiliary single stage, direct-coupled amplifier which is coupled in cascade with the A.2 amplifier to increase the gain available for the load cycle records.

All connections between equipment and oscillograph were made with twin screened cable and the screen was normally tied down with the return load. A single earth was provided at the oscillograph, the common terminal and the screening being at earth potential. The attenuator unit shown in Fig. 8 is used for the calibration of the toroid and integrating circuit. The method of calibration is described more fully in a following section.

Secondary Current and Condenser Charging Voltage

The integrator output is again taken to the A.1 amplifier and the charging voltage to the A.2 amplifier. Owing to the relatively large amplification used for the secondary current recording and to the proximity of the voltage leads to the control cabinet housing the electrical contactors, it is very difficult to avoid sudden large transients on the current records corresponding to the operation of contactors. It is best to keep the current leads well apart from the voltage leads as far as the oscillograph, so as to keep interference at a minimum.

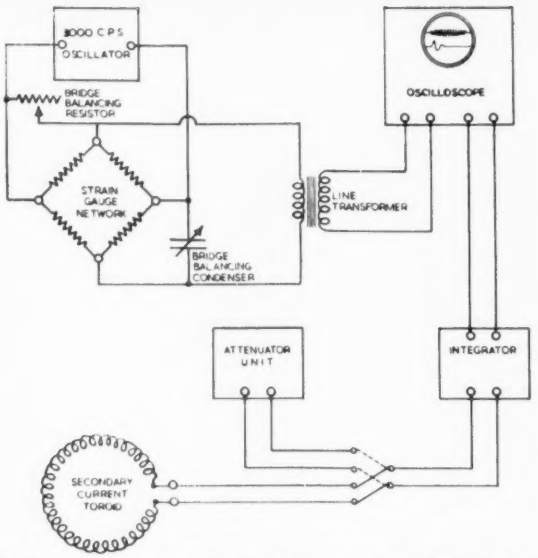


Fig. 8. Schematic circuit for secondary current and electrode load cycle measurement.

RECORDING EQUIPMENT

Oscillograph

The Cossor model 1049 double-beam oscillograph has been used for the measurements since both the A.1 and the A.2 amplifiers are direct coupled throughout. The A.1 amplifier comprises an input stage compensated for heater variations feeding into a phase splitter which in turn drives a push-pull output stage. The maximum gain available is about 900. The single valve A.2 amplifier has a gain of 25.

The amplifiers are fitted with attenuators which enable the gain to be varied by a number of fixed steps. In order that the amplitude of the secondary current trace on the Y.1 beam may be readily adjusted to fill the whole screen, an external attenuator unit has been made which enables the gain to be varied continuously. This stepless attenuator unit is placed in the circuit before the A.1 amplifier.

Photographic Recording

In all the measurements no time base is used and the cathode spots move only in the vertical direction. A commercially available 35 mm. camera has been extensively used for recording, using perforated recording paper for preliminary tests and safety film for the records. The film is continuously moving and film speed can be 4, 12, or 36 in. per second. The drive is by synchronous motor through a clutch which gives exceedingly rapid starting and stopping of the film.

This method of recording has much to recommend it from the point of view of simplicity and cost when many hundreds of records have to be taken. Recording on 35 mm. film does, however, limit the accuracy obtainable compared with methods in which much greater amplitudes are possible, e.g. single stroke time base method with recording on plate negatives.

RECORDS AND CALIBRATION

Records

Fig. 9 shows one example of each of the following records:

(*a*) Charging voltage.
(*b*) Electrode load cycle.
(*c*) Load cycle with short circuit secondary current.
(*d*) (*e*) Calibration traces for secondary current and load.

These particular records illustrate several interesting features:

(i) That there are marked oscillations in the top electrode on impact with the workpiece.
(ii) That current reversal in the secondary circuit can be large under certain conditions. The record shown was made under short circuit conditions for which current reversal is much greater than during normal welding.
(iii) That the times normally allowed for the charging of the condensers are relatively long and much greater than necessary, i.e. tip velocity could be increased without affecting condenser charging.

Calibration

Secondary Current.—The relation between toroid pick-up volts (e_s) and secondary current (i) is given by

$$e_s = \mathrm{A} \times n \times 0{\cdot}4\pi \times \frac{di}{dt} \times 10^{-8} \text{ volts}$$

where A is the area of one coil turn in sq. cm. and n the number of turns per cm.

For this voltage to be independent of the position and circumference of the toroid the latter must have a small cross-sectional area and the winding must form a complete loop around the electrode. One end of the toroid winding is brought back along the circumference to eliminate an undesirable effect of the toroid, i.e. the toroid itself forms a loop at right angles to the coil turns which would give rise to undesirable pick-up voltages.

The output of the particular coil used is 15·3 volts r.m.s. for a peak-to-peak sinusoidal current of 100,000 amps.

The method of calibration consists of obtaining an accurately known 50 c/s voltage input to the integrator by means of a potential divider and recording the C.R.O. trace under exactly the same conditions as when measuring the secondary current. The accurately known voltage is adjusted to give a deflection nearly the same as that obtained during the records, and the peak-to-peak deflections compared. The peak-to-peak current equivalent of the calibrating voltage is known from the coil constant (15·3 volts r.m.s. per 100,000 amps. peak-to-peak) so that the actual deflection on the records may be obtained in terms of current by simple proportion.

Electrode Load Cycle.—A Statimeter or similar device is placed between the electrodes and the signal developed from the bridge for a known static load is recorded, using the same conditions as for the load cycle records.

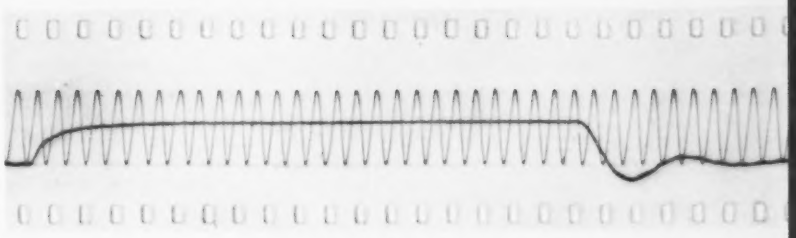
Electrode Tip Velocity.—The method of calibration used has been specifically developed to minimise the amount of pre-setting of the velocity unit prior to recording.

For this purpose a slip gauge of accurately known thickness is placed between the electrodes and the signal obtained, when the electrodes are closed upon the gauge, is recorded. A gauge of 0·2 ± 0·001 in. was used and the difference between the magnitude of the signal obtained with the gauge in position and that obtained during normal recording is equivalent to an electrode movement of 0·2 in. The magnitude of the calibrating trace is normally small compared with that of the actual record since the unit is preset to give near maximum deflection on impact, i.e. maximum deflection for a movement of 0·233 in.

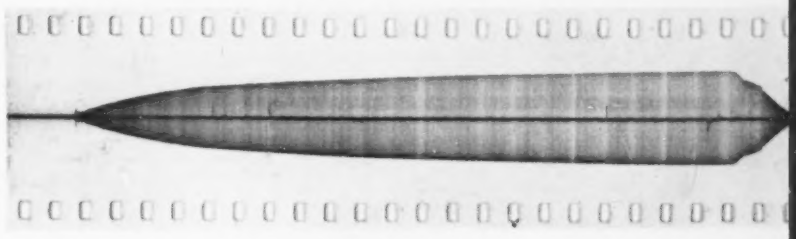
The tip velocity at impact is estimated by measuring the increase in amplitude of the modulated 1000 c/s. trace which occurs in the last 10 cycles (0·01 sec.) before impact. The distance covered in this time is determined from the known amplitude, equivalent to 0·2 in.

Secondary Voltage and Charging Voltage.—Calibration is easily obtained by feeding a known voltage signal into the amplifiers of the C.R.O. equipment and photographically recording the deflections. If a D.C. voltage is used for calibration, the zero line must be clearly indicated by superimposing the one beam on the other before applying the voltage, so that one beam can be used as a reference point.

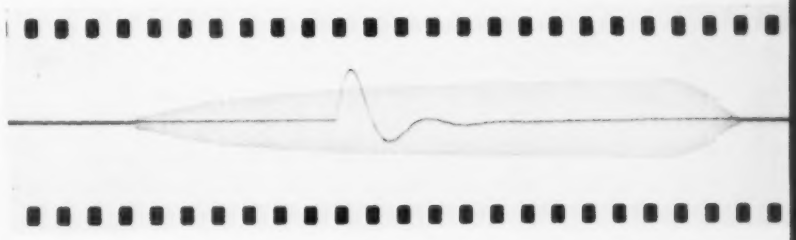
Time Calibration.—When one variable only is being measured, a 50-cycle timing calibration is normally applied to the second beam. It is not advisable to calculate times from the nominal film speed as this can vary appreciably due to the difficulty of accurately pre-setting the speed control. For a given setting, fluctuation in speed over a series of records is generally negligible, so that when no simultaneous time calibration is possible, no appreciable error is likely to result during a series of records by having a separate calibration for time.



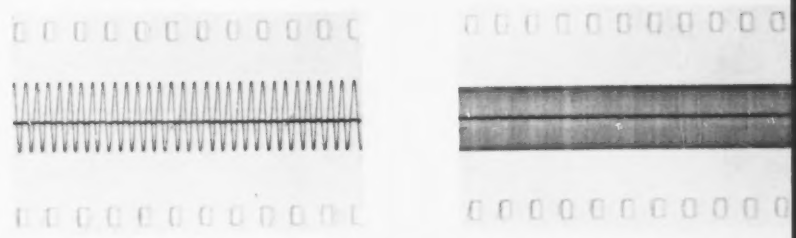
(*a*) Charging voltage with timing trace.



(*b*) Electrode load cycle.



(*c*) Electrode load cycle with short circuit secondary current.



(*d*) Current calibration. (*e*) Load calibration.

Fig. 9 (*a*—*e*). Examples of records.

MEASUREMENT OF RECORDS

All oscillograms are usually recorded on 35 mm. film and can be enlarged photographically if required. Normal practice has been to adjust the amplifiers to obtain near maximum deflection on the C.R.O. and to measure the deflection by means of a travelling microscope. Two verniers are provided on the microscope reading to either 0·05 or 0·005 mm., although the line width of the oscillograms makes the use of the fine vernier unnecessary. A special jig has been constructed to facilitate the accurate location of the film beneath the microscope and to maintain correct alignment of the film and microscope slide during the measurement of horizontal and vertical displacements.

An interesting point arises from the measurement of large numbers of records. It is imperative that any operator should not spend more than about one hour at a time on measurements, otherwise the consequent eye strain can introduce large errors into the measured values. The film must be adequately illuminated from beneath and this feature is incorporated in the locating jig. Further, it is important to ensure that all zero lines are clearly marked, so that there can be no doubt from where the displacements are to be measured.

ESTIMATED ACCURACY OF MEASUREMENTS

Secondary Current

Currents from 30,000 to 50,000 amps. (to nearest 500 amps.).
Currents greater than 60,000 amps. (to nearest 1,000 amps.).

Electrode Load Cycle

Loads up to 2,500 lb. (to nearest 50 lb.).
Loads from 2,500 to 6,000 lb. (to nearest 100 lb.).

Charging Voltage

Up to 250 volts (to nearest 5 volts).
250 to 500 volts (to nearest 10 volts).

Tip Velocity

Measured to nearest 0·2 in. per sec.

APPENDIX I

THE CATHODE FOLLOWER INTEGRATOR

Description of Action

A practical circuit for the integrator is shown in Fig. 10 which also includes the stabilised H.T. supply. It will be noted that the triode of Fig. 3 has been replaced by a pentode of fundamentally greater amplification but connected into the circuit as a triode. Since a valve only conducts current in one direction, the current must be increased and decreased from the datum of a steady current to obtain an A.C. output. Therefore with zero input a steady current flows through r_c and the 16μF condenser is necessary to prevent the steady voltage thus produced across r_c from appearing in the output. The action of the integrating circuit, of course, is not altered by a steady voltage across the condenser with zero input. The 1·5 K resistor provides the necessary steady bias voltage to ensure that the valve works in the correct part of its characteristic curve. The 1000μF condenser short-circuits this resistor to A.C. so that it does not interfere with the action of the valve as already described.

Testing of Integrator

In the absence of suitable equipment, calibration was obtained by comparing the performance of the cathode follower integrator with that of the simple R-C integrator of time constant about 50 times the period of the discharge. The main difficulty in assessing the performance in this manner was to decide the particular frequencies involved in the secondary pulse of the condenser discharge machine. It was estimated from the theoretical data and previous experience that discharge times of about 1/10th or 1/8th of a second would be produced in one machine and of about $\frac{1}{4}$ to $\frac{1}{2}$ a second in the other machine. These times were for one complete cycle, including one forward and one reverse pulse. It should be noted that the control circuit of this equipment is such that all reverse pulses or oscillations are delivered to the weld and there is no means of blocking-off parts of the discharge cycle. The equivalent sinusoidal wave was, therefore, assumed to be 8 c/s for the one machine and 2 c/s for the other machine. A value of R equal to one megohm and C of 5μF was used for the R-C integrator to give accurate integration.

The calculation of the errors involved in the R-C circuit is given below:

If ϕ is the phase angle between input and output voltages, then

$$\tan \phi = -\omega CR = -2\pi f CR$$

$$\simeq 250 \text{ for } f = 8 \text{ c/s and} \simeq 63 \text{ for } f = 2 \text{ c/s},$$

so that $\phi = 89{\cdot}8$ deg. ($f = 8$) and $89{\cdot}1$ deg. ($f = 2$)

The phase error is thus only 0·2 deg. and 0·9 deg. respectively and, since $\sin \phi$ is very nearly 1, the error in magnitude is negligible.

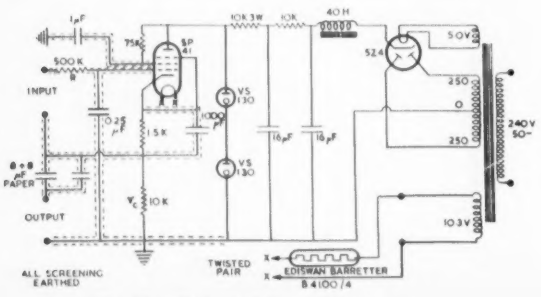


Fig. 10. Cathode follower integrator.

It will be seen that the basic assumption underlying the selection of R-C value for the condenser discharge current wave is that of fundamental frequency, i.e. that if it is satisfactory for 8 c/s sinusoidal wave, it will be equally satisfactory for the particular current waves of about 1/8th second duration given in the secondary circuit of the condenser discharge machine. It was shown practically that the time constant of the R-C circuit could be reduced to about $\frac{1}{4}$ of a second before appreciably altering the wave shape of the integrated signal for the machine. It was also shown that no difference could be detected between the current waves as recorded by the simple R-C circuit (time constant 5 secs.) or the cathode follower as shown in Fig. 10.

Consideration of the Errors in the Cathode Follower Integrator

Sources of Error.—There are three sources of error:

(i) The 1000μF grid-bias by-pass condenser does not completely short-circuit the grid-bias resistor.

(ii) The impedance of the 16μF condenser is not negligible and hence there is a voltage drop across it.

(iii) The cathode voltage does not exactly follow the grid voltage as there must be a small change in the voltage between the grid and the cathode to produce a change in the valve current.

Effect of Errors.—These errors appear both directly and indirectly. By "directly" is meant that the error appears as a difference between the voltage of the output and the voltage across the integrating condenser C. By "indirectly" is meant that the error appears as an insufficient "cancelling out" in the input circuit of the voltage across the integrating condenser.

Basic Assumption.—Calculation of the errors is based on the assumption of a sinusoidal voltage input of the same frequency as that of the welding discharge.

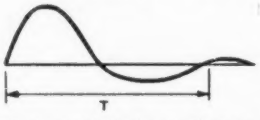


Fig. 11.

Fig. 11 shows the type of discharge that has been obtained, the period T being less than 0·5 secs. ($f \simeq 2$ c/s) in the extreme case for the high capacity, condenser discharge machine. Errors are calculated for a frequency of 2 c/s, the errors being reduced at higher frequencies.

Calibration.—The integrator is calibrated each time it is used. The calibration consists of obtaining a known 50 c/s voltage input to the integrator by means of an accurate potential divider and taking a photograph of the trace on the C.R.O. under the same conditions as when measuring the welding current.

Hence any errors in the integrator that are independent of frequency are the same at 50 c/s as at 2 c/s and therefore do not appear as errors in the measurement.

Error due to By-pass Condenser (Direct Error (a)).

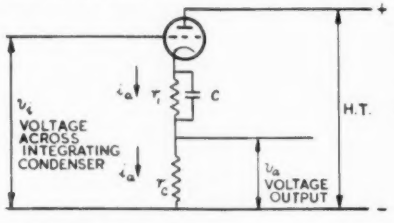


Fig. 12*a*.

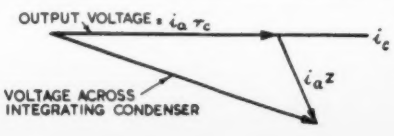


Fig. 12*b*.

Z = impedance of r_1 and C in parallel (see Fig. 12*a*) and can be shown to be

$$\frac{r_1 X_c}{r_1^2 + X_c^2} \quad (X_c - jr_1)$$

X_c being the reactance of C.

Where $r_1 = X_c$

$$Z \simeq \frac{r_1 X_c}{r_1^2} \times (X_c - jr_1).$$

$$Z \simeq \frac{X_c}{r_1} \times (X_c - jr_1).$$

$$\therefore Z \simeq \frac{X_c^2}{r_1} - jX_c$$

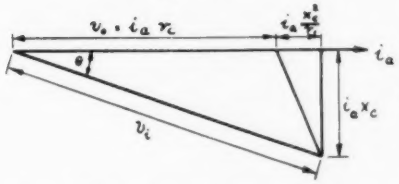


Fig. 12*c*.

With C = 1000μF f = 2 c/s, r_c = 10K, r_1 = 1·5K.

X_c = 79·6 ohms $\frac{X_c^2}{r_1}$ = 4·23 ohms.

The small X_c at right angles to r_c will have a negligible effect.

Hence the error in magnitude

$$\frac{X_c}{r_1} \div r_c \times 100 \text{ per cent.}$$

$\propto X_c^2$ approx.

Phase error = θ

$$\simeq \tan^{-1} \frac{X_c}{r_c} \propto X_c \text{ approx.}$$

In this case error in magnitude

$$\simeq \frac{4{\cdot}23}{10K} \times 100 \text{ per cent.}$$

$$\simeq 0{\cdot}042 \text{ per cent.}$$

Phase error = 0·46 deg. lead of the output volts on the true value.

Error due to Voltage Drop across the 16μF *Condenser* (*Direct Error* (*b*)).—The output of the integrator is assumed to be connected to a D.C. amplifier with an input resistance of r_3.

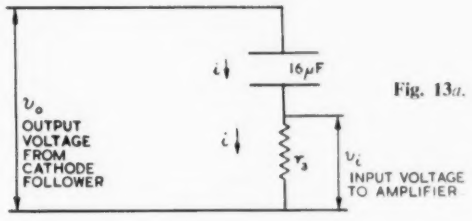


Fig. 13*a*.

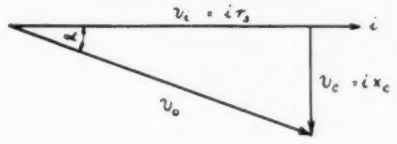


Fig. 13*b*.

Phase error = α

$$= \tan^{-1} \frac{V_c}{V_i}$$

$$= \tan^{-1} \frac{X_c}{r_3}$$

Error in magnitude = $V_o - V_i$.

With C = 16μF, f = 2 c/s, r_3 = 500 K,

X_c = 5K

The effect of 5K at right angles to 500K is much less than 1 per cent. Hence the error in magnitude is negligible.

Phase error = $\tan^{-1} \frac{5K}{500K}$

= 0·6 deg. lead of the voltage input to the amplifier on the output voltage of the cathode follower.

Errors due to Change in Grid-Cathode Voltage (*Direct Error* (*c*)).

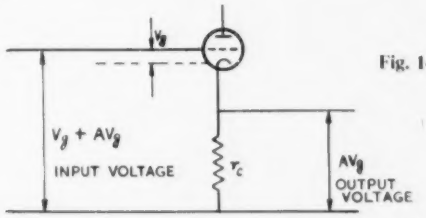


Fig. 14.

Considering Fig. 14, if the amplification of the stage is A, a change of V_g in the grid cathode-voltage will produce a change of AV_g across r_c. Hence the change of input voltage must have been

$$V_g + AV_g.$$

Hence the output differs from the input by V_g.

$$\text{Error per cent.} \simeq \frac{V_g}{AV_g} \times 100 \text{ per cent.}$$

$$\simeq \frac{1}{A} \times 100 \text{ per cent.}$$

Using the usual formula for the amplification of a stage, we have:

$$A = \frac{\mu r_c}{r_a + r_c}.$$

$$\text{Error per cent.} = \frac{r_a + r_c}{\mu r_c} \times 100 \text{ per cent.}$$

For this error to be low, $\frac{r_a}{\mu}$ must be low; but $\frac{\mu}{r_a}$ = mutual conductance.

Hence a valve with a large mutual conductance should be chosen.

With a 1·5K grid resistor, μ = 65, and r_a = 18·5K for a S.P. 41 valve.

$$\text{Hence error per cent.} = \frac{18{\cdot}5K + 10K}{65 \times 10K} \times 100 \text{ per cent.}$$

= 4·4 per cent.

There is no phase change. Since this error is independent of frequency, it will be the same at 50 c/s as at 2 c/s. Hence the calibration at 50 c/s eliminates the direct error. However, an indirect error is caused.

Indirect Errors (see Figs. 15*a* and 15*b*).—Indirect errors are caused by errors *a* and *c*. Total direct errors produced by *a* and *c* are a phase shift of 0·46 deg. lead and a reduction in magnitude of 4·4 per cent.

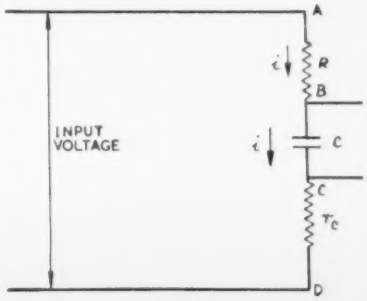


Fig. 15*a*.

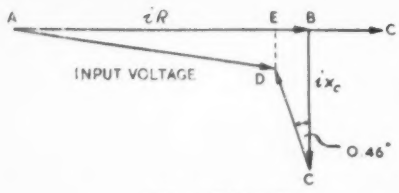


Fig. 15*b*.

$$ED \simeq BC - CD$$
$$\simeq 4{\cdot}4 \text{ per cent. } BC$$
$$\frac{BC}{AB} = \frac{iX_c}{iR} = \frac{X_c}{R}$$
$$\therefore ED \simeq 4{\cdot}4 \text{ per cent. } \frac{X_c}{R} \text{ . AB.}$$

With C = 0·25μF, f = 2 c/s, R = 500K
X_c = 318K
ED = 0·028 AB.

$$\text{Phase error} \simeq \tan^{-1}\frac{ED}{AB}$$
$$\simeq 1{\cdot}6 \text{ deg. lead of voltage across R on input voltage.}$$

$$BE = CD \sin 0{\cdot}46$$
$$\simeq BC \sin 0{\cdot}46$$
$$\simeq \frac{X_c}{R} AB. \sin 0{\cdot}46$$

$$\text{Error per cent.} \simeq \frac{BE}{AB} \times 100 \text{ per cent.}$$
$$\simeq \frac{X_c}{R} \sin 0{\cdot}46 \times 100 \text{ per cent.}$$
$$\simeq 0{\cdot}51 \text{ per cent. reduction in magnitude.}$$

In the case considered, error e causes the majority of this indirect error.

Total Error Produced.—

	Phase	Magnitude
Direct (*a*)	0·46 deg. lead	0·04 per cent. reduction
(*b*)	0·60 deg. lead	Negligible
(*c*)	None	Eliminated by calibration
Indirect	1·6 deg. lead	0·51 per cent. reduction
Total	2·7 deg. lead	0·55 per cent. reduction

Conclusion.—The errors, with the present values of circuit components and with a minimum frequency of 2 c/s, are within the permissible value. They have been calculated for the worst possible case with existing equipment and, since the majority of pulses will be of higher frequency than 2 c/s, the actual practical errors will be generally less than the calculated figures given above.

APPENDIX II

A DOUBLE BEAM LOAD UNIT FOR THE STATIC CALIBRATION OF ELECTRODE TIP LOAD

Design

For measurement of the static load, a hydraulic unit (Statimeter) has been used, but the instrument available was limited to a maximum load of 2200 lb. An accurate unit was therefore required for loads outside the range of this instrument. The "Statimeter" type of instrument is accurate for most purposes provided the applied load is axial and is maintained axial during the test, but if insufficient care is taken, appreciable errors may arise in the resulting measurements. It was appreciated that in designing a new instrument, alignment difficulties should be kept to a minimum.

A double beam cantilever unit was constructed with three points of application for maximum loads of 6,500, 4,000 and 3,000 lb.

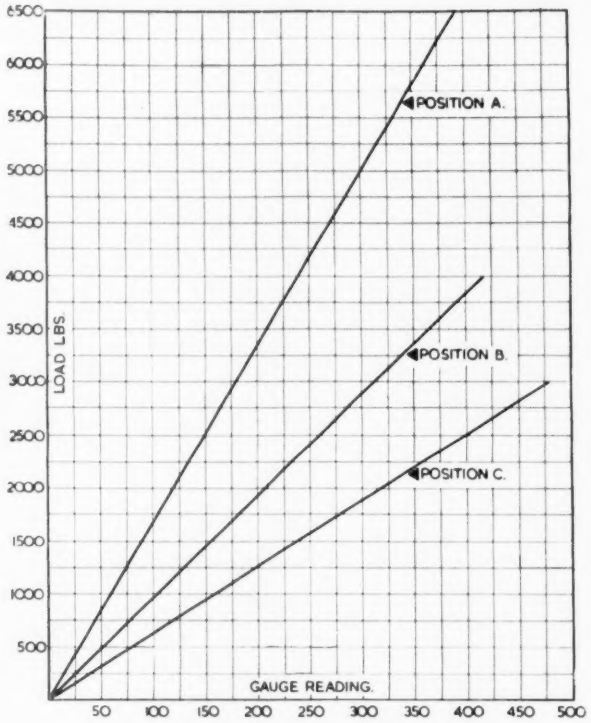


Fig. 16. Calibration chart for double beam unit.

Construction

The unit was machined in one piece from a block of mild steel, each beam being approximately 2 in. wide by $1\frac{1}{4}$ in. thick and about 9 in. overall length. One beam was shortened by 0·5 in. in order to provide space for attachment of the dial gauge. The overall depth at the fixed end was 3 in. and the width of the slot 0·5 in.

Cylindrical hardened-steel inserts with exposed end face cupped to $\frac{5}{16}$ in. radius were fitted into accurately bored holes in both top and bottom beams. The inserts thus defined accurately the position of the loading points and provided seatings for $\frac{5}{8}$ in. diameter hardened steel balls. Adapters were made to locate on the electrode and the steel balls. Hardened steel inserts were used in the adapters, the opposite face of each (one being required for the top and one for the bottom electrode) being machined to fit the standard face taper of the $1\frac{1}{2}$ in. diameter electrodes. The use of radiused inserts and steel balls ensured the accurate application of load and facilitated initial alignment to obtain axial loading.

A standard Mercer model "Beta" dial gauge was used graduated 0-100 and reading in 0·0001 in divisions. The position of the back lug was at right angles to the normal position to facilitate mounting on the top beam.

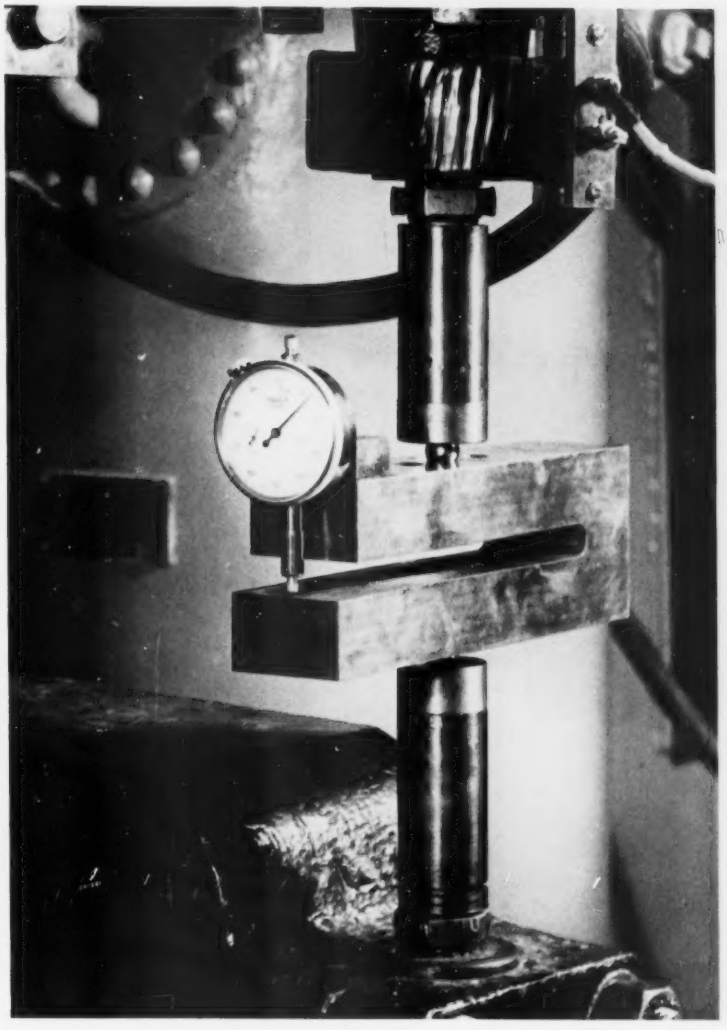
Calibration

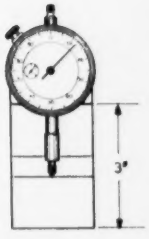
The beam load unit was calibrated by the Cambridge University Engineering Laboratories and the results are plotted in Fig. 16. It will be seen that the deflection obtained is directly proportional to the applied load for each loading position and that the results can be represented by three straight lines passing through the origin. The reproducibility of results is particularly good and the sensitivity is high, e.g. one division (1/10,000 in.) representing 16·6, 9·6 and 6·3 lb. for the 6,500, 4,000 and 3,000 lb. ranges respectively.

DOUBLE BEAM LOAD UNIT FOR MEASUREMENT OF ELECTRODE TIP LOAD.

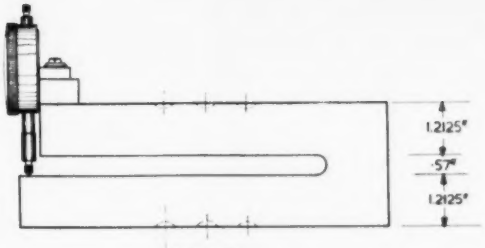
(See Appendix II of report on The Measurement of Spot Welding Machine Variables)

Illustration of equipment between welding electrodes of resistance welding machine, and drawings showing the general lay-out of the gauge.

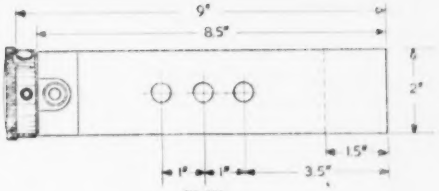




END VIEW



SIDE VIEW



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